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MANNED LUNAR LANDING MODE COMPARISON [redacted]

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OCTOBER 24, 1962

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OFFICE OF SYSTEMS

OFFICE OF MANNED SPACE FLIGHT

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON 25, D.C.

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TABLE OF CONTENTS

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INTRODUCTION

On July 11, 1962, the National Aeronautics and Space Administration announced its decision to base its studies, planning and procurement for lunar exploration primarily on the lunar orbit rendezvous mode while continuing studies on the earth orbital and direct flight modes, subject to confirmation at the time industry proposals to build the Lunar Excursion Module were finally evaluated. Certain additional studies were also to be completed by that time.

This report summarizes the result of recent studies of the possible application of a 2-man capsule to the earth orbit rendezvous and direct-flight modes. It is concluded that the lunar orbit rendezvous mode is the best choice for achieving a manned lunar landing mission before the end of the decade.

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MANNED LUNAR LANDING MODE COMPARISON

One of the major factors in the selection of a mode for the manned lunar landing program is a comparison of the several modes being considered with a series of technical criteria which establish mission feasibility and identify unique considerations. The prime technical criteria are physical realizability, mission safety and mission success probability. These technical criteria must be balanced against time and cost to arrive at the mission objectives. The mode selection study of July 30[1] demonstrated that both the Lunar Orbit Rendezvous (LOR) and Earth Orbit Rendezvous (EOR) modes were feasible with adequate weight margins, and that the 3-man C-5 direct ascent mode was undesirable because of small performance margins and high developmental risks. Subsequent studies have been conducted on 2-man capsules which might be used in either the C-5 direct flight or the EOR mode. Results of these studies (summarized in Appendix A) show that the 2-man C-5 direct flight mode is only feasible with cryogenic propulsion systems in all spacecraft stages, or with smaller performance margins than we deem desirable at this point in a program. The 2-man capsule would either increase the weight margins for EOR or allow simpler propulsion systems to be utilized throughout the spacecraft. These improvements are not sufficient to make EOR the preferred mode.

All of the sub-systems required to implement each mode can be developed within the scope of the manned lunar program. Estimates of the degree of developmental difficulty which might be encountered are qualitative, varying with the past experience of those conducting the analysis.

Comparisons of the 2-man lunar mission capsules with the present LOR approach lead to the conclusion that LOR is the preferred mode on the basis of technical simplicity, scheduling and cost considerations.

Mission Safety and Success Probabilities

The Mode Selection Report of July 30 demonstrated only minor differences in mission safety probabilities between EOR and LOR. Although LOR showed a higher probability of mission success than EOR (0.43 for LOR vs. 0.30 for EOR), the number of disasters per mission success for LOR was found to be slightly higher than the EOR figure (0.23 for LOR vs. 0.21 for EOR).

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[1] Manned Lunar Landing Program Mode Comparison Report. OMSF, 7/30/62 (CONFIDENTIAL)

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A subsequent analysis was conducted in greater detail, considering the LOR, EOR and C-5 direct flight modes. These studies (summarized in Appendix B) show that the overall mission success probability for EOR is 0.30, for C-5 direct 0.36, and for LOR 0.40. The number of disasters per mission success for EOR is 0.38, for C-5 direct 0.46, and the LOR 0.37. In particular, analysis has shown that LOR has the highest safety probability for operations in the vicinity of the moon. We believe that LOR is at least as safe as EOR while still enjoying a considerably higher overall mission success probability.

It could be stated that the LOR mode appears preferable based upon the calculated mission safety and success probabilities. However, the analyses leading to these results involve the estimation of the inherent reliability levels which will be reached by the individual sub-systems, and the detailed mechanization of the particular mode with respect to redundancy. These reliability predictions are not exact during the period when the detailed mechanization of the modes is still evolving. The relative results of both the mission success and safety probability calculations are sufficiently sensitive that the assumptions related to equipment performance can change the order of the results.

This leads to the conclusion that the difference between the modes from a mission safety standpoint as known at this point in time is the same order of magnitude as the uncertainty of the analysis. Reliability calculations, per se, are therefore not an adequate basis for choosing among the modes.

Major Differences Between Modes

The major technical differences between the modes lie in the following areas:

1. Cryogenic vs. storable stages in space;
2. Weight margin;
3. Lunar landing configurations;
4. Rendezvous.

These differences will be discussed in the following paragraphs.

Cryogenic vs. Storable Stages. The question of cryogenic vs. storable stages in space has two aspects: the reliability of the engines, and the storability of the stage. Most propulsion experts agree that a hypergolic, pressure-fed engine is simpler and, by implication, inherently more reliable than a pumped, regenerative cryogenic engine. Study of engine design confirms this. However, it is also agreed that engines reach inherent reliability only after an extended development program. The RL-10 hydrogen-oxygen engine has been in development for about four years; the storable engines are just starting their development cycle.

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Hence, at the time of the first lunar missions the cryogenic engine (if the RL-10 could be used in all space stages) might be closer to its inherent reliability than the storable engine. Judgment is again involved. The above arguments nonwithstanding, it is believed that storable engines will have reached a higher reliability than cryogenic engines at the time of the initial manned lunar attempts.

Space storability depends on the detailed thermal design of the stage. In space, the cryogenic fuels must be insulated to prevent excessive boil-off, the storable fuels insulated to prevent freezing. On the lunar surface, both cryogenic and storables are subject to boil-off during the lunar day, the problem being more severe for the cryogenics. During the lunar night, the cryogenics are subject to boil-off, the storables to freezing. Either stage will require careful design to insure compatibility with the environment. The problems appear to be more severe for the cryogenic fuels, especially since the storable fuels require an environment more compatible with the rest of the lunar vehicle.

The above considerations have led to the conclusion that storable propellants should be used for the Apollo applications. Storables are also the conservative choice on a performance basis, since it is possible from a weight standpoint to convert from storables to cryogenics at a later date, but the reverse is not true. Only LOR or 2-man EOR are compatible with the choice of storables in all space stages.

Weight Margin. The establishment of a proper weight margin is a factor in the realizability of the C-5 direct modes. Our experience has shown that weight levels for manned space vehicles have grown approximately 25% over initial "hard" estimates. This growth accommodates initial misestimates of hardware weights, equipment additions to increase mission capability, and design changes required by better definition of the environment. As a result of their studies, both Space Technology Laboratories and McDonnell Aircraft Corporation concluded that a 10% weight margin would be adequate to cover initial weight misestimations. Our experience dictates that an additional 15% be included for both increased mission capability and design changes which might result from increased environmental knowledge. The requirement for this increased weight margin does affect the possibility of using a storable return propulsion system for the 2-man C-5 direct mission. Considering all factors, the use of storable return propulsion would not provide sufficient assurance of success for the 2-man C-5 direct mode.

Lunar Landing Configuration. There are important differences in landing configuration between the Lunar Excursion Module (LEM) and the Command Module (CM). Although the landing can be achieved with either module, the LEM can be "optimized" for the lunar operations more readily than the CM which must also accommodate re-entry. The main factors are the internal arrangement of the capsules, and the degree of visibility provided the astronauts during the lunar landing phase. Landing the CM (particularly the 2-man version) would undoubtedly require use of television cameras to augment the pilot's field of view.

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In comparing the modes in the vicinity of the moon, both the C-5 direct and the EOR flight configurations must be staged during the terminal descent phase to reduce engine throttling requirements and landing gear loads. This staging requirement and the less desirable module arrangement are the factors in the direct landing mode which must be weighed against the requirement for rendezvous in the LOR mode. Continued study of alternate configurations has indicated that the simplicity of the LOR landing configuration is most desirable for early mission success.

In LOR, the re-entry and flight capsule can be separated from the lunar landing capsule during the course of the development program. Re-entry and flight requirements will affect the mass and moment of inertia of the re-entry and flight capsule, as well as the internal couch arrangement and the pilot displays. Astronaut position during lunar landing will affect the internal arrangement of the lunar landing capsule, and the visibility requirements can profoundly affect both capsule shape and structural integrity.

The industrial firms bidding on the LEM concluded that this separation of function was highly advantageous. (Their comments are summarized in Appendix C.)

Rendezvous. The major concern with respect to the Lunar Orbit Rendezvous arises from the requirement for rendezvous during the return phase of the mission. The mechanization of rendezvous has been studied in detail, and the planned configuration provides a redundant rendezvous capability within the LEM for all equipment failures except those in the main propulsion system. A similar capability exists in the command module. Hence the rendezvous maneuver is backed up with essentially a fourfold redundant mechanization. The duplicate contact, both radar and optical, which can be established between CM and LEM before launch from the lunar surface and maintained until docking, assures adequate relative velocity and position information between the two craft. Although earth tracking will not participate directly in the lunar operation, earth-based antennas will monitor the maneuvers and will aid in certification of the ephemeris of the CM lunar orbit. Studies of the rendezvous implementation, and simulations conducted at NASA centers and industry facilities, have indicated that the rendezvous maneuver is less difficult than the lunar landing. Specifically, the rendezvous in lunar orbit is no more difficult than rendezvous in earth orbit. Indeed, the configuration of the LEM may actually make the lunar rendezvous easier for the astronauts to execute than an earth orbit rendezvous operation involving two C-5 vehicles.

Summary of Technical Considerations. The summation of these considerations leads to the conclusion that the conservative approach to the manned lunar mission dictates the use of a 25% weight margin for any new capsule design and the use of storable engines in space. This conclusion, in conjunction with analyses of the several modes, rules out all modes save LOR and 2-man EOR. After comparison of landing configurations and rendezvous mechanizations, we conclude that the technical trade-offs distinctly favor the LOR mode.

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Human Factors

A factor in the LOR mode which has been frequently mentioned is the effect of mission duration and stress on crew performance during the rendezvous maneuver. Our study of these factors is summarized in Appendix D, which concludes that "pilot performance is not a limiting factor for either direct or lunar orbit rendezvous missions" based on a survey of the applicable literature and available test data. Another consideration is that the stress which the astronauts will undergo during both lunar landing and earth re-entry is at least equivalent to that experienced during rendezvous. The time constants for both re-entry and landing maneuvers are set by the mission. The time constant for rendezvous is at the astronaut's discretion--several orbits may be used to accomplish the actual docking in an extreme case. Based on these considerations, we conclude that the human factors implications are not significant for purposes of selecting a preferred mode.

National Space Capability

Appendix E discusses the implications of the mode choice on National Space Capability. The conclusion is that the only payload requirements exceeding the C-5 escape capability of 90,000 pounds which have presently been defined are for manned space flights, and then only if the EOR mode is utilized for the lunar mission. The operational techniques and the specific hardware developed in either the LOR or EOR mode are similar, with the exception of the tanker and fueling technology required for EOR. LOR does require crew transfer techniques and the development of structural docking mechanisms. The development of fuel transfer techniques which may ultimately be required for a wide class of fluids in space (from earth storables to hydrogen), can be most efficiently carried out in an exploratory development program rather than as an in-line element of the manned lunar landing program. We conclude that, on balance, there is no significant difference between LOR and EOR from a national capabilities viewpoint.

Conclusions

Based on the results of the studies summarized in the Appendices and the above discussion, we conclude that:

(1) The C-5 direct flight mode requires cryogenic fuels and is marginal, even with a two-man capsule;

(2) Both the EOR and LOR modes are feasible;

(3) The reliability differences between LOR and EOR cannot be demonstrated conclusively by analysis at this time; however, LOR does appear to have higher mission probability of success at less risk to the astronauts;

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(4) The capability to design the LEM specifically for the lunar landing, and the desirability of performing the mission with a single C-5 launch are important advantages of the LOR mode, offsetting the lesser problems associated with lunar rendezvous;

(5) Human factor considerations are not significant in the mode selections; the addition of rendezvous to the requirement for lunar landing and re-entry does not add appreciably to crew stress or fatigue, or to the overall hazards of the mission;

(6) Both EOR and LOR provide the basis for projected national space requirements prior to the development of NOVA-class vehicles. The C-5 vehicle capability meets estimated payload requirements. LOR provides experience in personnel transfer between space vehicles as contrasted with fuel transfer in EOR.

The scheduling studies last June demonstrated that the LOR mode could accomplish the lunar mission at least six to fifteen months earlier than the EOR mode. The fact that we have pursued the LOR approach during the intervening months has widened the schedule difference. The reason for the increased schedule difference can be identified in terms of the number of tests which must be completed before a lunar mission can be attempted, and the difference in firing schedules. Because of the requirement for two launchings per mission, EOR can only perform a mission every three months. LOR, on the other hand, can launch a mission every two months, since it requires only a single C-5 launch. We are convinced that the time difference between the EOR and LOR modes is now at the very least one year, and most probably in excess of 18 months.

The original mode selection study indicated that the LOR mode was 10 to 15% less expensive than the EOR approach. This difference arises primarily from the extra cost of launch vehicles for the EOR mode. This conclusion is still valid.

In addition to both schedule and cost advantages, the LOR mode provides the cleanest management structure within the NASA organization. The interface between the spacecraft and launch vehicle is simpler, and the responsibilities of the Manned Spacecraft Center at Houston and the Marshall Space Flight Center at Huntsville are easily defined and provide minimum interfaces between items under development at the two Centers.

In conclusion, the studies conducted since June of this year, and the additional work done within NASA and industry on the LOR approach, have indicated that the LOR mode offers the best opportunity of meeting the U.S. goal of manned lunar landing within this decade.

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APPENDIX A

FEASIBILITY OF TWO-MAN DIRECT FLIGHT AND EOR MANNED LUNAR MISSIONS

1. Introduction

Based on our analysis of the Apollo Mode Comparison in July, 1962, it was decided to proceed with Apollo planning on the basis of the Lunar Orbital Rendezvous (LOR) mode. However, it was also decided to look further into alternate modes before making a final commitment to develop the Lunar Excursion Module required for LOR. This paper summarizes our analysis of 2-man Apollo missions employing both Direct Flight and Earth Orbital Rendezvous modes.

2. Capsule Weights

a. Basic Weights

Studies of 2-man Apollo spacecraft have been completed by North American Aviation, Inc. (NAA), Space Technology Laboratories, Inc. (STL) and McDonnell Aircraft Corporation (MAC). The results of these studies have been compared with the various 3-man spacecraft which were analyzed by NASA in the original Apollo Mode Comparison. Following is a tabulation of the basic weights for the various 3-man and 2-man configurations which have been studied to date:

Item	NAA* (3-man) (154"D)	NAA (2-man) (154"D)	STL* (3-man) (138"D)	STL (2-man) (123"D)	MAC (2-man) (125"D)
Command Module	6,635	5,264	5,058	3,917	4,269
Crew and Crew Systems	1,491	925	988	824	865
Service Module Equipment	3,000	2,379	2,354	2,086	1,837
Total	11,126	8,568	8,400	6,827	6,971

* Weights as used in original Mode Comparison

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The attached drawings indicate the configurations of the Command Modules and the corresponding crew positions for the STL (Enclosure 1) and MAC (Enclosure 2) 2-man capsules. It should be noted that the 2-man configurations suffer from limited crew space and restricted visibility, particularly during the critical phase of lunar touchdown.

b. Weight Margins

In estimating the total Command and Service Module weights to be used in computing overall system performance, some margin must be added to the basic capsule weights which have been estimated at this early stage in system development. The STL and MAC sub-system weights for the Command Module and associated Service Module equipment have been analyzed to compare the maximum and minimum weights resulting from combinations of these estimates. This analysis indicates that the combined Command Module-Service Module equipment weight estimates vary from +18% to -21% of the mean value of the STL and MAC estimates at this stage of design. Both STL and MAC stated that their current estimates are within 10% of the final equipment weights, should their systems be developed. While a margin of 10% may be realistic for development of aircraft or earth-satellites because of the relative wealth of experience data, experience thus far in the development of manned spacecraft is limited to the Mercury, Gemini and Apollo projects. In Mercury, the original estimates of spacecraft weights increased by 25% up to the time of the first Mercury flight, and the weights have increased by an additional 5% (to a total of 30%) as of the present time. The Gemini spacecraft weight was estimated at 5600 pounds in December, 1961; current estimates total approximately 7,000 pounds, indicating a growth during the intervening nine months of approximately 25%. In the Apollo project, which is still in the early design stage, capsule weight growth is presently within (but approaching) 25% of the original weight estimates. Based on the Mercury, Gemini and Apollo experience and on analysis of the available 2-man Apollo capsule designs, it is concluded that a margin of 15% should be added to the Apollo 3-man spacecraft weight estimates*, and 25% should be added to

* Enclosure 3 is a plot of Apollo weight growth since March 1962, when the Mode Comparison estimate (11,126 lbs) was made. Although the estimate rose to 13,210 lbs. in August, it is now down to 12,070 lbs, and a stronger weight control program is being implemented. Therefore, a 15% margin applied to the Mode Comparison basic estimate is still considered adequate.

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those for all other concepts because of the more preliminary nature of their estimates. These total percentage margins must provide not only for growth which may result as design proceeds under current guidelines, but they must also provide for growth due to modification of current design guidelines to accommodate added mission requirements and uncertainties in knowledge of the environment. Applying these margins to the basic capsule weights listed above, the following values have been used in determining injected spacecraft weights for the various modes.

NAA (3-man)	NAA (2-man)	STL (3-man)	STL (2-man)	MAC (2-man)
12,795 lbs.	10,710 lbs.	9,716 lbs.	8,118 lbs.	8,200 lbs.

(Note: These weights do not include Service Module reaction control propellant, which is accounted for in mass fraction computations)

3. Total Spacecraft Weights at Injection

a. In computing total injection weights for the various modes, the velocity requirements have been re-analyzed since the original mode comparisons was completed in July, 1962. The revised V's are slightly higher than those previously used, resulting from both a refinement of earlier calculations and an increase in velocity reserve from 5% to 10%. This added reserve has been included to provide for off-nominal system operation (failure situations), uncertainties in current knowledge of system requirements, and flexibility in carrying out mission objectives. The following tabulation lists the values of V currently estimated as required for Direct Flight/EOR and for LOR:

	DF/EOR	LOR
Translunar Midcourse	300 ft/sec	300 ft/sec
Retro to Lunar Orbit	3130	3130
Lunar Orbit Plane Change (6^{o})	100	100
Separation of LEM	-	5
Transfer to descent trajectory	123	373
Descent to Hover	5831	5961
Hover	715	700

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	DF/EOR	LOR
Lunar Launch	5980	5985
2^{o} Plane Change on Launch	-	75
Rendezvous of LEM/CM	-	196
Emergency Rendezvous of CM with LEM	-	455
Exit from Lunar Orbit to Return Trajectory	3592	3610
Transearth Mid-course	300	300

b. In computing the spacecraft injection weights, the following values of specific impulse and mass fraction were used for the various propulsion systems considered:

	Isp (sec)	Mass Fraction
Mid-course		
Pressure-fed hypergolic	315	0.82
Retro to Lunar Orbit and Descent to Hover		
Pressure-fed hypergolic	310	0.875
Pressure-fed cryogenic	420	0.784
Pump-fed cryogenic	440	0.856
Hover and Touchdown	310/300 (variable)	0.85
Pressure-fed hypergolic		
Lunar Launch and Injection To Earth		
Pressure-fed hypergolic	315	0.85
Pressure-fed cryogenic	420	0.77
Pump-fed cryogenic	440	0.80

c. The following table compares injected weights of 3-man and 2-man configurations for a variety of spacecraft propulsion systems, based on the guidelines used in the earlier Mode Comparison.

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Propulsion System*		Injected Spacecraft Weight (lbs)			
Braking Module	Service Module	3-man(NAA)	2-man(NAA)	3-man(STL)	2-man(STL-MAC)
Pr-St	Pr-St	216,305	181,047	164,313	138,714
Pr-Cr	Pr-St	184,525	154,447	140,181	118,347
Pu-Cr	Pr-St	153,495	128,475	116,618	98,460
Pu-Cr	Pr-Cr	128,304	107,391	98,191	82,901
Pu-Cr	Pu-Cr	112,961	94,588	85,788	72,434

*Pr = Pressure-fed
Pu = Pump-fed

St = Earth-storable propellants
Cr = Cryogenic propellants

4. <u>Capabilities of C-5 Launch Vehicles</u>

a. The current C-5 performance limit is 90,000 lbs. injected into an earth-to-moon trajectory. This value is based on the use of five F-1 engines (@1,500,000 lbs. thrust) in the S-IC stage; five J-2 engines (@200,000 lbs. thrust) in the S-II stage and one J-2 engine in the S-IV B stage. Various proposals have been advanced for up-rating C-5 performance, including:

(1) Up-rating F-1 thrust by 20% to 1.8 million pounds, primarily by increasing chamber pressure.

(2) Up-rating J-2 thrust by 5% to 210,000 pounds, primarily by increasing flow rate, and increasing specific impulse 2 to 3% by increasing the expansion ratio.

(3) Increasing the number of engines in the S-IC and S-II stages.

Computer calculations indicate that up-rating of the C-5 could theoretically provide injected weight capabilities of 93,000 to 110,000 pounds, by using various combinations of the proposed methods.

b. Major development problems and program delays are anticipated if an up-rating program should be implemented.

Delays are anticipated primarily in the engine test program and in the availability of facilities because of modifications which would be required. Following are some specific examples:

(1) At present, the F-1 has undergone 185 static test firings, of an estimated 500 required (1300 were required for the H-1 engine). The F-1 program has slipped six months during

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the 45 months it has been under development. Tests to date in stepping up from 1200K to 1500K thrust have indicated a tendency to instability; increasing chamber pressure to that required for 1800K could well create serious instability problems, with attendant schedule slippages. However, a 5% to 10% up-rating of the F-1 might be possible without major delays, provided additional funds were made available. Additional funds would also be required for modification of F-1 test stands and gas generating equipment.

(2) The J-2 engine has currently undergone 90 static tests, of which approximately 20 have provided significant data and the pre-flight test program has slipped six months to date. The J-2 program is just entering the phase where problem areas can be expected in operation at the presently planned thrust level. Analysis indicates that an increase in the J-2 thrust level of a few percent may be possible by design modifications, particularly in the liquid hydrogen turbopump. However, it also appears that the resulting increase in thrust level would cause a reduction in by-pass flow and consequently reduce the propellant utilization in the stage. The overall performance improvement might therefore be marginal. It is estimated that a J-2 up-rating program could not profitably be started for 12 to 18 months and would add at least 18 months to the present J-2 test schedule.

(3) Adding engines to the S-IC stage would result in a substantially larger vehicle diameter, which in turn would require major modifications to existing and planned facilities. At Michoud, a new manufacturing and final assembly building would be required at an estimated cost of $20 million and 16 months. Re-sizing test stands at the Mississippi Test Facility would add several months to the MTS availability schedule.

c. It is concluded that, although some up-rating of C-5 might be possible with additional time, money and performance uncertainty, the presently estimated 90,000 lb. performance limit provides the best basis for Apollo mission planning. The corresponding performance limit for two C-5 vehicles operating in the EOR mode is 150,000 lbs.

5. Conclusions

Based on current estimates of spacecraft weights, including realistic weight margins and propulsion system performance values, and accepting the C-5 performance values, it is concluded that:

a. A Direct Flight, 2-man Apollo mode using storable propellants is not feasible under the assumptions listed above but might be feasible if weight margins were reduced or if C-5 were up-rated by 10%.

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c. An Earth Orbital Rendezvous, 2-man Apollo mode is feasible using storable propellants both for deboost from lunar orbit and for return to earth.

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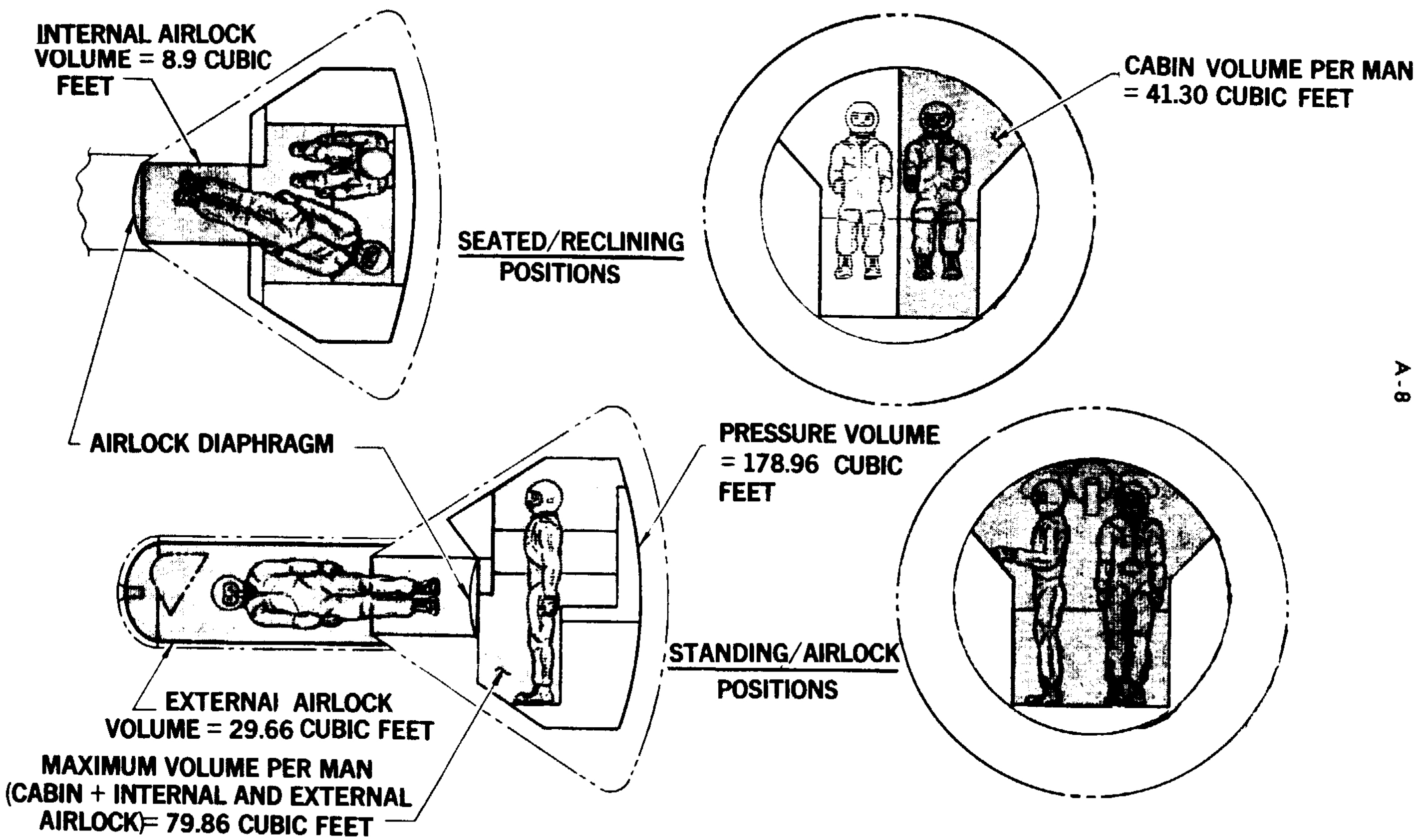
SPACE TECHNOLOGY LAB
2-MAN APOLLO CAPSULE



COMMAND MODULE CREW STATIONS AND VOLUMES (123 INCH DIAMETER)

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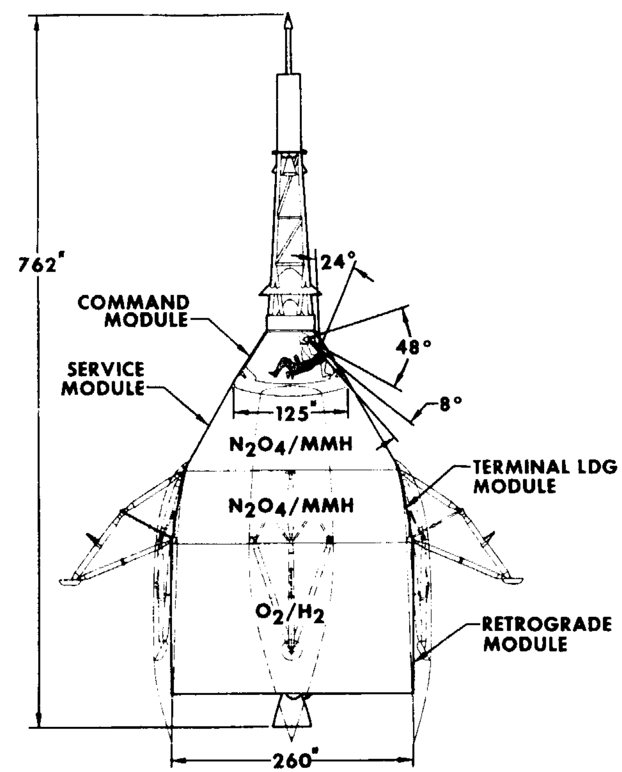
MC DONNELL AIRCRAFT CORP
2-MAN APOLLO SPACECRAFT



VOLUME	(185 FT.^{3})
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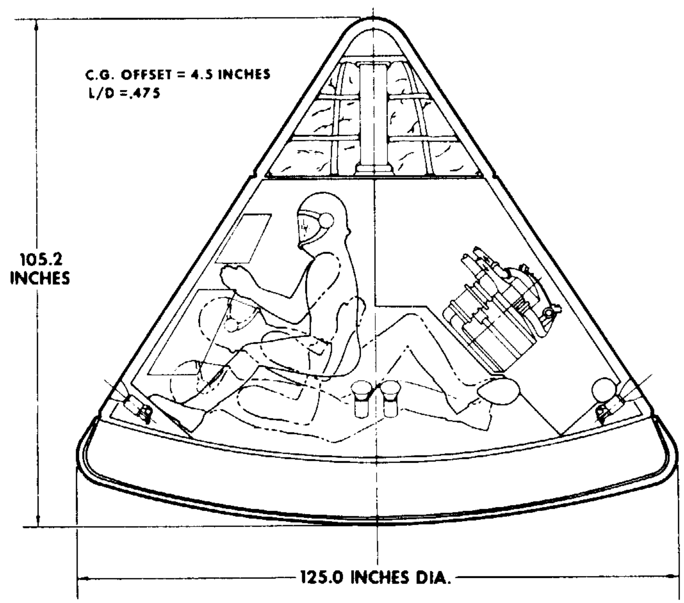
EQUIPMENT	100 FT.^{3}
RECOVERY SYSTEM	12 FT.^{3}



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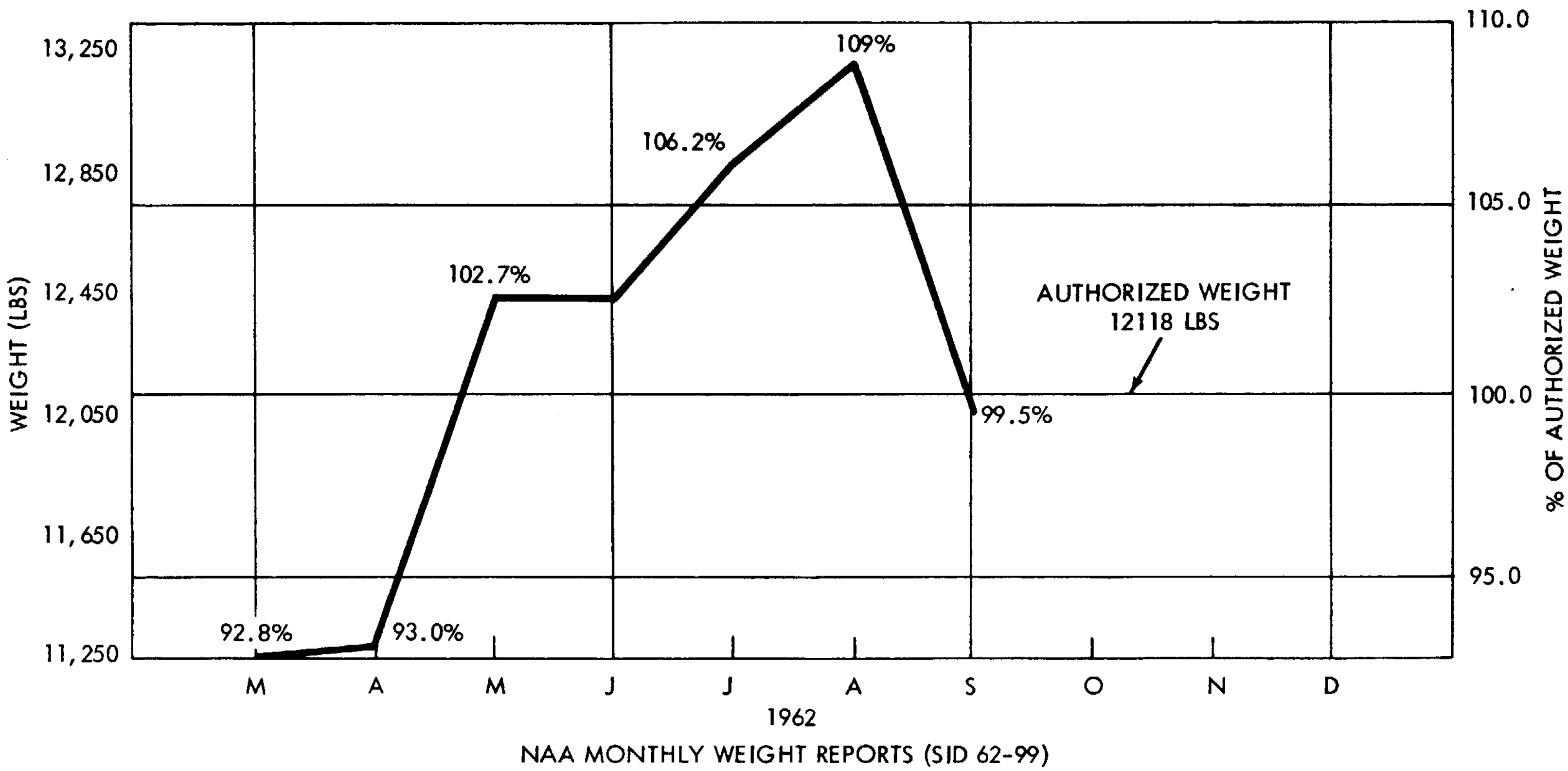
WEIGHT STATUS---MARCH--SEPT. 1962
NAA APOLLO COMMAND MODULE and SERVICE MODULE EQUIPMENT



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APPENDIX B

DETAILED RELIABILITY AND SAFETY CALCULATIONS FOR LOR, 2-MAN EOR, AND 2-MAN C-5 DIRECT FLIGHT MODES

Summary

The results of a detailed analysis of safety and reliability factors for the LOR, 2-man EOR and 2-man C-5 direct flight modes are summarized in Table I. The significant parameters are the "over-all mission success probability" and "disasters per mission success". From a mission success standpoint, LOR ranked highest with a 0.40 probability, 2-man C-5 next with 0.36, and EOR last with 0.30. The EOR success probability reflects the requirement for successful launch of two C-5's to complete the mission. On the basis of disasters per mission success, EOR and LOR are essentially equal (0.37 for EOR and 0.38 for LOR) with 2-man C-5 (0.46) inferior to both.

The over-all mission safety probability is somewhat misleading, because it involves both the abort success probability at each step, and the probability of having reached the step. Hence EOR, because of the lower probability of having accomplished the dual launch, shows a higher safety probability per mission attempt than LOR since for some attempts (when the tanker fails to reach earth orbit) the astronauts are in no danger.

A more meaningful quantity is safety in vicinity of the moon. This is the probability that, having reached the moon, the astronauts will return safely to earth. The calculations show little difference between the modes, LOR being slightly safer at 0.87 than EOR at 0.86 and 2-man C-5 at 0.85.

The temptation is to draw the conclusion from these calculations that LOR is the preferable mode considering both mission success and disasters per mission. However, the important fact the figures demonstrate is that the rendezvous requirement in LOR is but a small addition to a complex mission. The reliability decrement caused by the extra step can be kept small by proper mechanization of the system, and can be more than offset by the simplicity possible in other required steps, such as lunar descent and landing.

The assumptions made in the analysis and the details of the calculations are contained in the following sections.

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TABLE I

This table summarizes the results of the detailed analysis of safety and reliability factors for the LOR, 2-man EOR, and 2-man C-5 direct flight modes:

	LOR	2-MAN C-5 D	2-MAN EOR
Over-all mission success probability	0.4043	0.3643	0.2968
Over-all mission safety	0.8500	0.8312	0.8878
Disasters/mission success	0.3710	0.4633	0.3780
Safety (vicinity of moon)	0.8711	0.8457	0.8560
Reliability (vicinity of moon)	0.7994	0.7111	0.8018
Guidance reliability (vicinity of moon)	0.9267	0.9172	0.9172
Propulsion reliability (vicinity of moon)	0.8959	0.7956	0.8971
Attitude control reliability (vicinity of moon)	0.9915	0.9985	0.9985
Human factors reliability (vicinity of moon)	0.9918	0.9934	0.9934
Life support equipment reliability (vicinity of moon)	0.9995	0.9996	0.9996
Mechanical reliability (vicinity of moon)	0.9848	0.9884	0.9884
Communications reliability (vicinity of moon)	0.9993	0.9999	0.9999
Crew and science equipment reliability (vicinity of moon)	0.9950	0.9950	0.9950

[redacted]

[redacted]

Assumptions

1. Propulsion systems:

   A. Direct mode uses three RL10A engines, pumped, for lunar orbit retro maneuver, for orbit transfer maneuver, and for lunar descent to hover point.

   B. Direct mode uses one throttlable (3.5:1) earth-storable, pressurized engine for hover and touchdown, lunar launch, and lunar escape.

   C. Direct mode is a two-stage spacecraft, LBM and SM.

   D. LOR uses one constant thrust, earth-storable, pressurized engine for lunar orbit retro maneuver and for lunar escape maneuver.

   E. LOR uses one throttlable (3.5:1), earth-storable, pressurized engine for orbit transfer, lunar descent, hover and touchdown.

   F. LOR uses one constant thrust, earth-storable, pressurized engine for lunar launch and rendezvous maneuver. Rendezvous midcourse maneuver is accomplished by the LEM attitude control jets.

   G. LOR SM is single stage
      LOR LEM is 2-stage

   H. EOR uses one constant thrust, earth-storable, pressurized engine for lunar orbit retro maneuver, orbit transfer maneuver, and lunar descent maneuver.

   I. EOR uses one throttlable (3.5:1) earth storable, pressurized engine for hover and touchdown, lunar launch, and lunar escape.

   J. Generally similar considerations as cited for the 2-man C-5 direct flight mode, plus the differences attributable to the requirement for operations in earth orbit.

   K. Propulsion system reliability is divided into "ignition," "burn," and "shutoff" reliabilities using LLVPG values. "Burn" unreliability is taken to be proportional to burning time as follows:

[redacted]

Transfer to synchronous ellipse	15%
Transfer to Hohmann ellipse	4%
Rendezvous maneuver	7%
Lunar descent maneuver	90%
Hover and touchdown	10%
Lunar orbit retro and lunar escape	100%

2. Attitude control systems

   A. All attitude control systems have completely redundant thrust chambers and feed systems. Basic reliability per ignition-burn-shutoff with redundancy is 0.999998. Twenty-four firings are required per maneuver.

Navigation in lunar orbit	12 maneuvers
Navigation in transfer orbit	4 maneuvers
Orientation	2 maneuvers
CM navigation during mission	82 maneuvers
Docking maneuver	40 maneuvers

3. Structures

   A. Separation or docking mechanical reliability 0.9928 (LLVPG)

   B. Landing gear reliability 0.9920

4. Guidance and Navigation

   A. Loss of primary guidance requires abort until lunar landing is accomplished.

   B. Direct landing requires TV because of visibility problem. LOR does not.

   C.

Platform and computer reliability	= 0.9926
TV reliability	= 0.9950
Radar reliability	= 0.9950
Altimeter reliability	= 0.9950
Backup guidance reliability	= 0.9500

   D. LEM and CM equipment are redundant for navigation in lunar orbit before landing.

5. Communications

   A. Communications from LEM to CM are required for lunar launch through docking, and for all lunar surface operations.

[redacted]

B. Communications reliability is 0.9900 per system and systems are fully redundant.

6. Life support equipment

A. Life support equipment reliability = 0.9900 per system and systems are fully redundant.

7. Human factors

A. One man can perform each operation alone.

B. In "real time" operations (e.g., touchdown) men are not redundant.

C. In leisurely operations (e.g., navigation) men are redundant.

D. Both men must be independently effective in lunar surface operations.

E. Reliability of astronauts assuming optimum training:

a. After 72 hours of 3-shift operation (LOR)
   0.9980 for real time operations
   0.9995 for leisurely operations
b. After 72 hours of 2-shift operations (Direct)
   0.9960 for real time operations
   0.9990 for leisurely operations

F. Astronaut reliability does not degrade further during lunar operations.

8. Trajectory operations

A. LOR uses synchronous orbit for landing.
B. Direct uses Hohmann orbit for landing.
C. LOR uses Hohmann orbit for rendezvous.
D. Direct launches into elliptic lunar orbit which is not circularized before escape.
E. In the LOR rendezvous maneuver the CM rendezvous capability is reundant only for "burn" failures of the LEM launch propulsion system.

9. Safety considerations

A. Twenty per cent of propulsion failures are immediately catastrophic.

[redacted]

B. Abort from any point in the translunar phase of the trip is accomplished by executing the entire lunar escape maneuvers in the required direction and re-entering the atmosphere. The neglect of midcourse maneuvers in this calculation is approximately offset by including the entire burning time of the Service Module. The approximation is probably somewhat optimistic.

C. Abort from lunar orbit is accomplished by executing the normal return maneuvers with appropriate equipment degraded.

D. The mission is successful if lunar surface operations are completed and the crew returns safely to Earth.

E. Loss of the platform and computer, which is treated as a single subsystem, degrades the reliability of subsequent guidance operations to 0.9500.

LOR Mode - Reliability and Safety Analysis

	Normal Mode		Abort Mode		Normal Guidance CM			Backup Guidance CM			Normal Guidance LEM			Backup Guidance LEM		
	Subsys. Rel.	Step Rel.	Subsys. Rel.	Step Rel.	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point
1. C-5 First Stage		.8778			.1002	.9990[A]	49	--	--	--	--	--	--			
Fuel System	.9961															
Oxidizer System	.9923															
Hydraulic Control (per engine)	.9981															
Auxiliary Power	1.0000															
Pneumatic Control	.9976															
Electronics & Guid.	.9882															
Airframe & Separation	.9982															
Engines (each)	.9816															
2. C-5 Second Stage		.8301			.1406	.9919[B]	49									
Fuel System	.9978															
Oxidizer System	.9945															
Hydraulic Control (per engine)	.9977															
Auxiliary Power	1.0000															
Electronics & Guid.	.9745															
Airframe & Separation	.9982															
Prop. Utilization	.9976															
Engines (each)	.9732															
3. C-5 Third Stage, 1st burn		.9297			.0597	.9919[B]	49									
Fuel System	.9978															
Oxidizer System	.9945															
Dual burn Control, Fuel	.9989															
..............., oxid.	.9992															
Hydraulic Control	.9977															
Auxiliary power	1.0000															
Electronics & guid.	.9827															
Airframe & Separation	.9991															
Prop. Utilization	.9976															
Attitude Control	.9930															
Roll Control	.9991															
Engines	.9732															
Engine, dual burn cont.	.9945															

[redacted]

	Normal Mode Subsys. Rel.	Normal Mode Step Rel.	Abort Mode Subsys. Rel.	Abort Mode Step Rel.	Normal Guidance CM Abort Prob.	Normal Guidance CM Abort Rel.	Normal Guidance CM To Point	Backup Guidance CM Abort Prob.	Backup Guidance CM Abort Rel.	Backup Guidance CM To Point	Normal Guidance LEM Abort Prob.	Normal Guidance LEM Abort Rel.	Normal Guidance LEM To Point	Backup Guidance LEM Abort Prob.	Backup Guidance LEM Abort Rel.	Backup Guidance LEM To Point
4.																
Earth Orbit Coast		.9870			.0130	.9919[B]	49									
Attitude Control	.9994															
Platform & Computer	.9926															
Sextant & Scanning Tel.	.9950															
Human Factors	1.0000															
Life Support Equip.	.9999															
5.																
Orient for Injection		.9925			.0001	.9919[B]	49	.0074	.7944[C]	51						
Attitude Control	.9999															
Platform & Computer	.9926															
Human Factors	1.0000															
6.																
C-5, 3rd Stage, 2nd burn		.9297			.0597	.9718[D]	49									
Fuel System	.9978															
Oxidizer System	.9945															
Dual burn control, fuel	.9989															
................, oxid.	.9992															
Hydraulic control	.9977															
Auxiliary Power	1.0000															
Electronics & guid.	.9827															
Airframe & Separation	.9991															
Prop. Utilization	.9976															
Attitude Control	.9930															
Roll Control	.9991															
Engine	.9732															
Engine, dual burn cont.	.9945															
7.																
LEM Orientation		.9760			.0166	.9718[D]	49	.0074	.7815[E]	51						
Attitude Control, SIVB	.9990															
Attitude Control, SM	.9980															
Platform & Computer, SIVB	.9926															
Plat. & Computer, CM	.9926															
Human Factors	.9990															
Mechanical	.9946															

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	Normal Mode		Abort Mode		Normal Guidance CM			Backup Guidance CM			Normal Guidance LEM			Backup Guidance LEM		
	Subsys. Rel.	Step Rel.	Subsys. Rel.	Step Rel.	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point
8. Navigate, translunar Coast		.9894			.0031	.9735^F	49	.0074	.7828^G	51						
Attitude Control	.9994															
Plat. & Computer	.9926															
Sextant	.9975															
Human Factors	1.0000															
Life Support Equip.	.9999															
9. Orient for Midcourse Man.		.9925			.0001	.9735^F	49	.0074	.7828^G	51						
Attitude Control	.9999															
Platform & Computer	.9926															
Human Factors	1.0000															
10. Midcourse Man.-Main Prop.		.9873			.0041	.9735^F	49	.0074	.7828^G	51						
Ignition	.9960															
Burn (2% burn time)	.9996															
Shutoff	.9991															
Plat. and Computer	.9926															
11. Navigate, translunar Coast		.9894			.0031	.9735^F	49	.0074	.7828^G	51						
Attitude Control	.9994															
Platform & Computer	.9926															
Sextant	.9975															
Human Factors	1.0000															
Life Support Equip.	.9999															
12. Orient for Midcourse Man.		.9925			.0001	.9735^F	49	.0074	.7828^G	51						
Attitude Control	.9999															
Platform & Computer	.9926															
Human Factors	1.0000															
13. Midcourse Man.-Main Prop.		.9873			.0041	.9735^F	49	.0074	.7828^G	51						
Ignition	.9960															
Burn (2% burn time)	.9996															
Shutoff	.9991															
Flat. and Computer	.9926															

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[redacted]	Normal Mode		Abort Mode		Normal Guidance CM			Backup Guidance CM			Normal Guidance LEM			Backup Guidance LEM		
	Subsys. Rel.	Step Rel.	Subsys. Rel.	Step Rel.	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point
14. Navigate, translunar Coast		.9894			.0031	.9735[F]	49	.0074	.7828[G]	51						
Attitude Control	.9994															
Plat. & Computer	.9926															
Sextant	.9975															
Human Factors	1.0000															
Life Support Equip.	.9999															
15. Orient for Midcourse Man.		.9925			.0001	.9735[F]	49	.0074	.7828[G]	51						
Attitude Control	.9999															
Plat. & Computer	.9926															
Human Factors	1.0000															
16. Midcourse Man.-Att. Control		.9916			.0010	.9735[F]	49	.0074	.7828[G]	51						
Attitude Control	.9990															
Plat. & Computer	.9926															
17. Navigate, translunar Coast		.9894			.0031	.9735[F]	49	.0074	.7828[G]	51						
Attitude Control	.9994															
Plat. and Computer	.9926															
Sextant	.9975															
Human Factors	1.0000															
Life Support Equip.	.9999															
18. Orient for Midcourse Man.		.9925			.0001	.9735[F]	49	.0074	.7828[G]	51						
Attitude Control	.9999															
Plat. & Computer	.9426															
Human Factors	1.0000															
19. Midcourse Man.-Att. Control		.9916			.0010	.9735[F]	49	.0074	.7828[G]	51						
Attitude Control	.9990															
Plat. & Computer	.9926															
20. Navigate for lunar retro man.		.9868			.0057	.9735[F]	49	.0074	.7828[G]	51						
Attitude Control	.9994															
Plat. & Computer	.9926															
Sextant	.9975															
Human Factors	.9999															
Life Support Equip.	.9999															
Scanning Telescope	.9975															

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	Normal Mode		Abort Mode		Normal Guidance CM			Backup Guidance CM			Normal Guidance LEM			Backup Guidance LEM		
	Subsys. Rel.	Step Rel.	Subsys. Rel.	Step Rel.	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point
21. Orient for lunar retro man.		.9924			.0002	$.9735^F$	49	.0074	$.7828^G$	51						
Attitude Control	.9999															
Platform & Computer	.9926															
Human Factors	.9999															
22. Lunar orbit retro Man.		.9691			.0208	$.9982^H$	35	.0074	$.4152^I$	51						
Ignite	.9960															
Burn	.9811															
Shutoff	.9991															
Platform & Computer	.9926															
23. Navigate in lunar orbit		.9990			.0007	1.0000	35	.0002	$.4152^I$	51						
Attitude Control	.9994															
Platform & Computer	.9999															
Sextant & Scanning Tel.	.9999															
Human Factors	.9999															
Life Support Equip.	.9999															
24. Sep. LEM & Orient for trans.		.9906									.0002	$.9906^I$	35	.0074	$.9415^K$	35
Mechanical	.9982															
Attitude Control, LEM	.9999															
Platform & Computer, LEM	.9926															
Human Factors, LEM	.9999															
25. LEM Transfer orbit Man.		.9845			.0001	$.9982^L$	31	.0001	$.3878^M$	51	.0063	$.9982^N$	31	.0074	$.7888^O$	35
Ignition	.9960															
Burn	.9970															
Shutoff	.9991															
Platform & Computer, LEM	.9926															
Platform & Computer, CM	.9999															
Attitude Control, CM	.9999															
26. Navigate, transfer orbit		.9870			.0001	$.9982^L$	31	.0001	$.3878^M$	51	.0054	$.9982^N$	31	.0074	$.7888^O$	35
Attitude Control, LEM	.9998															
Plat. & Computer, LEM	.9926															
Sextant & Tel., LEM	.9950															
Human Factors, LEM	.9999															
Life Support Equip, LEM	.9999															
Platform & Computer, CM	.9999															
Sextant & Teles., CM	.9999															

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[redacted]	Normal Mode		Abort Mode		Normal Guidance CM			Backup Guidance CM			Normal Guidance LEM			Backup Guidance LEM		
	Subsys. Rel.	Step Rel.	Subsys. Rel.	Step Rel.	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point
27.																
Orient for Descent Man.		.9922			.0001	.9982[L]	31	.0001	.3878[M]	51	.0003	.9982[N]	31	.0074	.7888[O]	35
Attitude Control, LEM	.9999															
Computer & Platform, LEM	.9926															
Human Factors, LEM	.9999															
Platform & Computer, CM	.9999															
Attitude Control, CM	.9999															
28.																
Descent Maneuver		.9484			.0001	1.0000	30	.0001	.3777[Q]	51	.0310	1.0000	30	.0074	.7301[R]	35
Ignition	.9960															
Burn	.9801															
Shutoff	.9991															
Platform & Computer, LEM	.9926															
Human Factors, LEM	.9980															
Radar, LEM	.9950															
Altimeter, LEM	.9950															
Landing gear	.9920															
Platform & Computer, CM	.9999															
Sextant & Teles., CM	.9999															
29.																
Lunar Surface, operations		.9776			.0092	1.0000	30	.0070	.3777[Q]	51	.0060	1.0000	30			
Communications LEM	.9999															
Crew Equip. & Science	.9950															
Life Support Equip. LEM	.9999															
Human Factors, LEM	.9990															
Attitude Control, CM	.9961															
Platform & Computer, CM	.9930															
Sextant & Teles. CM	.9952															
Human Factors, CM	.9995															
Life Support Equip., CM	.9999															
Communications, CM	.9999															
30.																
Lunar Launch		.9740		.9257												
Mechanical	.9982		.9982													
Ignite	.9960		.9960													
Burn	.9811		.9811													
Shutoff	.9991		.9991													
Computer & Platform	.9996		.9500													
Communications	.9999		.9999													

[redacted]

	Normal Mode		Abort Mode		Normal Guidance CM			Backup Guidance CM			Normal Guidance LEM			Backup Guidance LEM		
	Subsys. Rel.	Step Rel.	Subsys. Rel.	Step Rel.	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point
31. Orbit Determination		.9986		.9400												
Attitude Control	.9998		.9998													
Platform & Computer, Sextant & Scan. Tel., Radar	.9991		.9405													
Life Support Equip.	.9999		.9999													
Human Factors	.9999		.9999													
Communications	.9999		.9999													
32. Orient for Rendez. Man.		.9993		.9497												
Attitude Control	.9999		.9999													
Platform & Computer	.9996		.9500													
Human Factors	.9999		.9999													
Communications	.9999		.9999													
33. Rendezvous Maneuver		.9944		.9404												
Ignition	.9960		.9960													
Burn	.9999		.9999													
Shutoff	.9991		.9991													
Platform & Computer	.9994		.9500													
Radar			.9950													
Communications	.9999		.9999													
34. Docking Maneuver		.9906		.9414												
Attitude Control, LEM	.9980		.9980													
Platform & Computer, LEM	.9996		.9500													
Human Factors, LEM	.9980		.9980													
Communications	.9999		.9999													
Attitude Control, CM	.9990		.9990													
Platform & Computer, CM	.9996		.9996													
Human Factors, CM	.9980		.9980													
Mechanical	.9982		.9982													
35. Orient for Escape Maneuver		.9976		.9481												
Mechanical	.9982		.9982													
Attitude Control	.9999		.9999													
Platform & Computer	.9996		.9500													
Human Factors	.9999		.9999													

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	Normal Mode		Abort Mode		Normal Guidance CM			Backup Guidance CM			Normal Guidance LEM			Backup Guidance LEM		
	Subsys. Rel.	Step Rel.	Subsys. Rel.	Step Rel.	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point
36. Escape Maneuver		.9759		.9275												
Ignite	.9960		.9960													
Burn	.9811		.9811													
Shutoff	.9991		.9991													
Platform & Computer	.9996		.9500													
37. Navigate, Transearth Coast		.9983		.9492												
Attitude Control	.9994		.9994													
Platform & Computer Sextant	.9991		.9500													
Human Factors	.9999		.9999													
Life Support Equip.	.9999		.9999													
38. Orient for Midcourse Man.		.9994		.9498												
Attitude Control	.9999		.9999													
Platform & Computer	.9996		.9500													
Human Factors	.9999		.9999													
39. Midcourse Man.-Main Prop.		.9943		.9450												
Ignition	.9960		.9960													
Burn	.9996		.9996													
Shutoff	.9991		.9991													
Platform & Computer	.9996		.9500													
40. Navigate, Transearth Coast		.9983		.9492												
Attitude Control	.9994		.9994													
Platform & Computer Sextant	.9991		.9500													
Human Factors	.9999		.9999													
Life Support Equip.	.9999		.9999													
41. Orient for Midcourse Man.		.9994		.9498												
Attitude Control	.9999		.9999													
Platform & Computer	.9996		.9500													
Human Factors	.9999		.9999													
42. Midcourse Maneuver-main Prop.		.9943		.9450												
Ignition	.9960		.9960													
Burn	.9996		.9996													
Shutoff	.9991		.9991													
Platform & Computer	.9996		.9500													

[redacted]

[redacted]

	Normal Mode		Abort Mode		Normal Guidance CM			Backup Guidance CM			Normal Guidance LEM			Backup Guidance LEM		
	Subsys. Rel.	Step Rel.	Subsys. Rel.	Step Rel.	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point
43.																
Navigate, transearth coast		.9983		.9492												
Attitude Control	.9994		.9994													
Platform & Control / Sextant	.9991		.9500													
Human Factors	.9999		.9999													
Life Support Equip.	.9999		.9999													
44.																
Orient for Midcourse Man.		.9994		.9498												
Attitude Control	.9999		.9999													
Platform & Computer	.9996		.9500													
Human Factors	.9999		.9999													
45.																
Midcourse Maneuver-Att.Cont.		.9986		.9490												
Attitude Control	.9990		.9990													
Platform & Computer	.9996		.9500													
46.																
Navigate transearth Coast		.9983		.9492												
Attitude Control	.9994		.9994													
Platform & Computer / Sextant	.9991		.9500													
Human Factors	.9999		.9999													
Life Support Equip.	.9999		.9999													
47.																
Orient for Midcourse Man.		.9994		.9498												
Attitude Control	.9999		.9999													
Platform and Computer	.9996		.9500													
Human Factors	.9999		.9999													
48.																
Midcourse Maneuver-Att. Cont.		.9986		.9490												
Attitude Control	.9990		.9990													
Platform & Computer	.9996		.9500													
49.																
Orient for Re-entry		.9974		.9480												
Mechanical	.9982		.9982													
Attitude Control	.9999		.9999													
Platform & Computer	.9996		.9500													
Human Factors	.9999		.9999													
50.																
Re-Entry		.9882		.9392												
Attitude Control	.9980		.9980													
Mechanical	.9982		.9982													
Platform & Computer	.9996		.9500													
Human Factors	.9960		.9960													

	Normal Mode		Abort Mode		Normal Guidance CM			Backup Guidance CM			Normal Guidance LEM			Backup Guidance LEM		
	Subsys. Rel.	Step Rel.	Subsys. Rel.	Step Rel.	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point
51. Recovery		.9990		.9990												

Overall Mission Success Probability	.4043
Overall Mission Safety	.8500
Disasters/Success	.3710
Safety (after step 21)	.8711

LOR NOTES:

A. Escape tower reliability = .9990
B. (Airframe and separation) (Orient for midcourse) (Midcourse maneuver, SM Engine)
C. (Airframe and separation) (Orient for midcourse, backup guidance) (Midcourse maneuver, SM Engine, backup guidance) (Orient for re-entry, backup guidance) (Re-entry backup guidance)
D. (Airframe and separation) (Orient for escape) (Escape maneuver)
E. (Airframe and separation) (Orient for escape, backup guidance) (Escape Maneuver, backup guidance) (Orient for re-entry, backup guidance) (Re-entry, backup guidance)
F. (Orient for escape) (Escape maneuver)
G. (Orient for escape, backup guidance) (Escape maneuver, backup guidance) (Orient for re-entry, backup guidance) (Re-entry, backup guidance)
H. (Separate LEM)
I. (Stage LEM) (Steps 35 through 50 with backup guidance)
J. (Re-orient LEM and dock)
K. Re-orient LEM and dock with backup guidance
L. Separate LEM landing stage
M. (Separate LEM landing stage) (Steps 31, 32 and 33) (Steps 34 thru 50 with backup guidance)
N. (Separate LEM landing stage)
O. (Separate LEM landing stage) (Steps 31 thru 34 with backup guidance)
P. (Separate LEM landing stage)
Q. (Separate LEM landing stage) (Steps 30 thru 33) (Steps 34 thru 50 with backup guidance)
R. (Separate LEM landing stage) (Steps 30 thru 34 with backup guidance)

[redacted]

C-5 Direct Reliability and Safety Analysis

	Normal Mode		Abort Mode		Normal Guidance CM			Backup Guidance CM			Normal Guidance LEM			Backup Guidance LEM		
	Subsys. Rel.	Step Rel.	Subsys. Rel.	Step Rel.	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point
1. C-5 First Stage		.8778			.1022	.9990[A]	48									
Fuel System	.9961															
Oxidizer System	.9923															
Hydraulic Con. (pereng)	.9981															
Auxiliary Power	1.0000															
Pneumatic Cont.	.9976															
Elect. & Guidance	.9882															
Airframe & Sep.	.9982															
Engines (each)	.9816															
2. C-5 Second Stage		.8301			.1406	.9919[B]	48									
Fuel System	.9978															
Oxidizer System	.9945															
Hydrau. Cont. (pereng)	.9977															
Auxiliary Power	1.0000															
Elect. & Guidance	.9745															
Airframe & Sep.	.9982															
Propellant Utiliz.	.9976															
Engines (each)	.9732															
3. C-5 Third Stage, 1st burn		.9297			.0597	.9919[B]	48									
Fuel System	.9978															
Oxidizer System	.9945															
Dual burn con., fuel	.9989															
........., oxidizer	.9992															
Hydrau. Control	.9977															
Auxiliary Power	1.0000															
Elec. & Guid.	.9827															
Airframe & Sep.	.9991															
Prop. Utilization	.9976															
Attitude Control	.9930															
Roll Control	.9991															
Engine	.9732															
Engine, dual burn con.	.9945															
4. Earth Orbit Coast		.9870			.0130	.9919[B]	48					[redacted]				
Attitude Control	.9994															
Plat. & Computer	.9926															
Sextant & Scann. tel.	.9950															
Human Factors	1.0000															
Life Support Equip.	.9999															

[redacted]

	Normal Mode		Abort Mode		Normal Guidance CM			Backup Guidance CM			Normal Guidance LEM			Backup Guidance LEM		
	Subsys. Rel.	Step Rel.	Subsys. Rel.	Step Rel.	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point
5. Orient for Injection		.9925			.0001	.9919[B]	48	.0074	.7977[C]	48						
Attitude Control	.9999															
Platform & Computer	.9926															
Human Factors	1.0000															
6. C-5, 3rd Stage, 2nd Burn		.9297			.0597	.9730[D]	46									
Fuel System	.9978															
Oxidizer System	.9945															
Dual burn Con., fuel	.9989															
........., oxidizer	.9992															
Hydraulic Control	.9977															
Auxiliary Power	1.0000															
Electronics & Guid.	.9827															
Airframe & Sep.	.9991															
Prop. Utilization	.9976															
Attitude Control	.9930															
Roll Control	.9991															
Engine	.9732															
Engine, dual burn con.	.9945															
7. Navigate, translunar coast		.9894			.0031	.9730[D]	46	.0074	.7825[E]	48						
Attitude Control	.9994															
Platform & Computer	.9926															
Sextant	.9975															
Human Factors	1.0000															
Life Support Equip.	.9999															
8. Orient for Midcourse Man.		.9925			.0001	.9730[D]	46	.0074	.7825[E]	48						
Attitude Control	.9999															
Platform & Computer	.9926															
Human Factors	1.0000															
9. Midcourse Man-Main Prop.		.9820			.0085	.9730[D]	46	.0074	.7825[E]	48						
Ignition	.9909															
Burn (2% burn time)	.9993															
Shutoff	.9991															
Platform & Computer	.9926															
10. Navigate, translunar coast		.9894			.0031	.9730[D]	46	.0074	.7825[E]	48						
Attitude Control	.9994															
Platform & Computer	.9926															
Sextant	.9975															
Human Factors	1.0000															
Life Support Equip.	.9999															

[redacted]

[redacted]	Normal Mode		Abort Mode		Normal Guidance CM			Backup Guidance CM			Normal Guidance LEM			Backup Guidance LEM		
	Subsys. Rel.	Step Rel.	Subsys. Rel.	Step Rel.	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point
11.Orient for Midcourse Man.		.9925			.0001	$.9730^D$	46	.0074	$.7825^E$	48						
Attitude Control	.9999															
Platform & Computer	.9926															
Human Factors	1.0000															
12.Midcourse Man-Main Prop.		.9820			.0085	$.9730^D$	46	.0074	$.7825^E$	48						
Ignition	.9909															
Burn (2% burn time)	.9993															
Shutoff	.9991															
Platform & Computer	.9926															
13.Navigate,translunar coast		.9894			.0031	$.9730^D$	46	.0074	$.7825^E$	48						
Attitude Control	.9994															
Platform & Computer	.9926															
Sextant	.9975															
Human Factors	1.0000															
Life Support Equip.	.9999															
14.Orient for Midcourse Man.		.9925			.0001	$.9730^D$	46	.0074	$.7825^E$	48						
Attitude Control	.9999															
Platform & Computer	.9926															
Human Factors	1.0000															
15.Midcourse Man.-Att. Cont.		.9916			.0010	$.9730^D$	46	.0074	$.7825^E$	48						
Attitude Control	.9990															
Platform & Computer	.9926															
16.Navigate,translunar coast		.9894			.0031	$.9730^D$	46	.0074	$.7825^E$	48						
Attitude Control	.9994															
Platform & Computer	.9926															
Sextant	.9975															
Human Factors	1.0000															
Life Support Equip.	.9999															
17.Orient for Midcourse Man.		.9925			.0001	$.9730^D$	46	.0074	$.7825^E$	48						
Attitude Control	.9999															
Platform & Computer	.9926															
Human Factors	1.0000															
18.Midcourse Man.-Att. Cont.		.9916			.0010	$.9730^D$	46	.0074	$.7825^E$	48				[redacted]		
Attitude Control	.9990															
Platform & Computer	.9926															

[redacted]

	Normal Mode		Abort Mode		Normal Guidance CM			Backup Guidance CM			Normal Guidance LEM			Backup Guidance LEM		
	Subsys. Rel.	Step Rel.	Subsys. Rel.	Step Rel.	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point
19. Navigate for lunar retro man.		.9868			.0057	$.9730^{D}$	46	.0074	$.7825^{E}$	48						
Attitude Control	.9994															
Platform & Computer	.9926															
Sextant	.9975															
Human Factors	.9999															
Life Support Equip.	.9999															
Scanning Telescope	.9975															
20. Orient for Lunar retro Man.		.9924			.0002	$.9730^{D}$	46	.0074	$.7825^{E}$	48						
Attitude control	.9999															
Platform & Computer	.9926															
Human Factors	.9999															
21. Lunar Orbit Retro Man		.9231			.0556	$.9982^{F}$	31	.0074	$.3946^{G}$	48						
Ignite	.9727															
Burn	.9585															
Shutoff	.9975															
Platform & Computer	.9926															
22. Navigate in lunar orbit		.9868			.0058	$.9982^{F}$	31	.0074	$.3946^{G}$	48						
Attitude Control	.9994															
Platform & Computer	.9926															
Sextant & Scann. Tel.	.9950															
Human Factors	.9999															
23. Orient for Transfer		.9924			.0002.	$.9982^{F}$	32	.0074	$.4157^{H}$	48						
Attitude Control	.9999															
Platform & Computer	.9926															
Human Factors	.9999															
24. Transfer orbit Maneuver		.9615			.0249	$.9982^{F}$	31	.0074	$.3946^{G}$	48						
Ignition	.9727															
Burn	.9984															
Shutoff	.9975															
Platform & Computer	.9926															
25. Navigate, transfer orbit		.9872			.0002	$.9982^{F}$	31	.0074	$.3946^{G}$	48						
Attitude Control	.9998															
Platform & Computer	.9926															
Sextant & Teles.	.9950															
Human Factors	.9999															
Life Support Equip.	.9999															

[redacted]

	[redacted]rmal Mode		Abort Mode		Normal Guidance CM			Backup Guidance CM			Normal Guidance LEM			Backup Guidance LEM		
	Subsys. Rel.	Step Rel.	Subsys. Rel.	Step Rel.	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point
26. Orient for Descent Man.		.9924			.0002	.9982[F]	32	.0074	.4157[H]	48						
Attitude Control	.9999															
Computer & Platform	.9926															
Human Factors	.9999															
27. Descent Maneuver		.9224			.0568	.9721[I]	31	.0074	.3651[H]	48						
Ignition	.9727															
Burn (90%)	.9626															
Shutoff	.9975															
Platform & Computer	.9926															
Radar	.9950															
28. Hover & Letdown Maneuver		.9622			.0158	.9721[I]	31	.0074	.3651[J]	48						
Mechanical	.9982															
Ignition	.9960															
Burn (10%)	.9980															
Shutoff	.9991															
Computer & Platform	.9926															
Human Factors	.9960															
Altimeter	.9950															
Landing Gear	.9920															
Television	.9950															
29. Lunar Surface Operations		.9928			.0071	.9739[K]	31									
Communications	.9999															
Crew & Science Equip.	.9950															
Life Support Equip.	.9999															
Human Factors	.9980															
30. Lunar Launch		.9739		.9253												
Mechanical	.9982		.9982													
Ignition	.9960		.9960													
Burn	.9806		.9806													
Shutoff	.9991		.9991													
Computer & Platform	.9996		.9500													
31. Orbit Determination		.9983		.9492												
Attitude Control	.9994		.9994													
Platform & Computer Sextant & Scann. Tel.	.9991		.9500													
Life Support Equip.	.9999		.9999													
Human Factors	.9999		.9999													

[redacted]

[redacted]

	Normal Mode		Abort Mode		Normal Guidance CM			Backup Guidance CM			Normal Guidance LEM			Backup Guidance LEM		
	Subsys. Rel.	Step Rel.	Subsys. Rel.	Step Rel.	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point
32. Orient for Escape Man.		.9994		.9498												
Attitude Control	.9999		.9999													
Platform & Computer	.9996		.9500													
Human Factors	.9999		.9999													
33. Escape Maneuver		.9754		.9270												
Ignite	.9960		.9960													
Burn	.9806		.9806													
Shutoff	.9991		.9991													
Platform & Computer	.9996		.9500													
34. Navigate, transearth coast		.9983		.9492												
Attitude Control	.9994		.9994													
Platform & Computer Sextant	.9991		.9500													
Human Factors	.9999		.9999													
Life Support Equip.	.9999		.9999													
35. Orient for Midcourse Man.		.9994		.9498												
Attitude Control	.9999		.9999													
Platform & Computer	.9996		.9500													
Human Factors	.9999		.9999													
36. Midcourse Man.-Main Prop.		.9943		.9450												
Ignition	.9960		.9960													
Burn	.9996		.9996													
Shutoff	.9991		.9991													
Platform & Computer	.9996		.9500													
37. Navigate, transearth coast		.9983		.9492												
Attitude Control	.9994		.9994													
Platform & Computer Sextant	.9991		.9500													
Human Factors	.9999		.9999													
Life Support Equip.	.9999		.9999													
38. Orient for Midcourse Man.		.9994		.9498												
Attitude Control	.9999		.9999													
Platform & Computer	.9996		.9500													
Human Factors	.9999		.9999													

[redacted]

[redacted]

	Normal Mode		Abort Mode		Normal Guidance CM			Backup Guidance CM			Normal Guidance LEM			Backup Guidance LEM		
	Subsys. Rel.	Step Rel.	Subsys. Rel.	Step Rel.	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point
39. Midcourse Man.-Main Prop.		.9943		.9450												
Ignition	.9960		.9960													
Burn	.9996		.9996													
Shutoff	.9991		.9991													
Platform & Computer	.9996		.9500													
40. Navigate, transearth coast		.9983		.9492												
Attitude Control	.9994		.9994													
Platform & Computer / Sextant	.9991		.9500													
Human Factors	.9999		.9999													
Life Support Equip.	.9999		.9999													
41. Orient for Midcourse Man.		.9994		.9498												
Attitude Control	.9999		.9999													
Platform & Computer	.9996		.9500													
Human Factors	.9999		.9999													
42. Midcourse Man.-Alt. Control		.9986		.9490												
Attitude Control	.9990		.9990													
Platform & Computer	.9996		.9500													
43. Navigate, transearth coast		.9983		.9492												
Attitude Control	.9994		.9994													
Platform & Computer / Sextant	.9991		.9500													
Human Factors	.9999		.9999													
Life Support Equip.	.9999		.9999													
44. Orient for Midcourse Man.		.9994		.9498												
Attitude Control	.9999		.9999													
Platform & Computer	.9996		.9500													
Human Factors	.9999		.9999													
45. Midcourse Man.-Attit. Con.		.9986		.9490												
Attitude Control	.9990		.9990													
Platform & Computer	.9996		.9500													

[redacted]

[redacted]

	Normal Mode		Abort Mode		Normal Guidance CM			Backup Guidance CM			Normal Guidance LEM			Backup Guidance LEM		
	Subsys. Rel.	Step Rel.	Subsys. Rel.	Step Rel.	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point
46. Orient for Re-entry		.9974		.9480												
Mechanical	.9982		.9982													
Attitude Control	.9999		.9999													
Platform & Computer	.9996		.9500													
Human Factors	.9999		.9999													
47. Re-entry		.9882		.9392												
Attitude Control	.9980		.9980													
Mechanical	.9982		.9982													
Platform & Computer	.9996		.9500													
Human Factors	.9960		.9960													
48. Recovery		.9990		.9990												
Overall Mission Success Probability				.3643												
Overall Mission Safety				.8312												
Disasters/Success				.4633												
Safety (after step 21)				.8457												

[redacted]

NOTES: C-5 Direct Reliability and Safety Analysis

A. Escape tower reliability = .9990
B. (Airframe and separation) (Orient for midcourse) (Midcourse maneuver, SM engine)
C. (Airframe and separation) (Orient for midcourse, backup guidance) (Midcourse maneuver, SM engine, backup guidance) (Orient for re-entry, backup guidance) (Re-entry backup guidance)
D. (Airframe and separation) (Orient for escape) (Escape maneuver)
E. (Airframe and separation) (Orient for escape, backup guidance) (Escape maneuver, backup guidance) (Orient for re-entry, backup guidance) (Re-entry, backup guidance)
F. (Orient for escape) (Escape Maneuver)
G. (Orient for escape, backup guidance) (Escape maneuver, backup guidance) (Orient for re-entry, backup guidance) (Re-entry, backup guidance)
H. (Separate LEM)
I. (Stage LEM) (Steps 35 thru 50 with backup guidance)
J. (Reorient LEM and dock)
K. (Reorient LEM and dock with backup guidance)
L. Separate LEM landing stage
M. (Separate LEM landing stage) (Steps 31, 32, and 33) (Steps 34 through 50 with backup guidance)
N. (Separate LEM landing stage)
O. (Separate LEM landing stage) (Steps 31 thru 34 with backup guidance)
P. (Separate LEM landing stage)
Q. (Separate LEM landing stage) (Steps 30 thru 33) (Steps 34 thru 50 with backup guidance)
R. (Separate LEM landing stage) (Steps 30 thru 34 with backup guidance)

[redacted]

2-Man EOR Reliability and Safety Analysis

	Normal Mode		Abort Mode		Normal Guidance CM			Backup Guidance CM			Normal Guidance LEM			Backup Guidance LEM		
	Subsys. Rel.	Step Rel.	Subsys. Rel.	Step Rel.	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point
1. C-5 First Stage, tanker		.8778			.1222	1.0000	56									
Fuel System	.9961															
Oxidizer System	.9923															
Hydraulic Con. per eng.	.9981															
Auxiliary Power	1.0000															
Pneumatic Control	.9976															
Electronics & Guid.	.9882															
Airframe & Sep.	.9982															
Engines, each	.9816															
2. C-5 2nd. Stage, tanker		.8301			.1699	1.0000	56									
Fuel System	.9978															
Oxidizer System	.9945															
Hydraulic Con. per eng.	.9977															
Auxiliary Power	1.0000															
Electronics & Guid.	.9745															
Airframe & Separation	.9982															
Prop. Utilization	.9976															
Engines, each	.9732															
3. Tanker Coast		.9920			.0080	1.0000	56									
Attitude Con. System	.9994															
Platform & Computer	.9926															
4. C-5 1st Stage, manned veh.		.8778			.1002	.9990A	53									
Fuel System	.9961															
Oxidizer System	.9923															
Hydrau. Con. per eng.	.9981															
Auxiliary Power	1.0000															
Pneumatic Control	.9976															
Electronics & Guid.	.9882															
Airframe & Sep.	.9982															
Engines, each	.9816															

[redacted]

[redacted]

	Normal Mode Subsys. Rel.	Normal Mode Step Rel.	Abort Mode Subsys. Rel.	Abort Mode Step Rel.	Normal Guidance CM Abort Prob.	Normal Guidance CM Abort Rel.	Normal Guidance CM To Point	Backup Guidance CM Abort Prob.	Backup Guidance CM Abort Rel.	Backup Guidance CM To Point	Normal Guidance LEM Abort Prob.	Normal Guidance LEM Abort Rel.	Normal Guidance LEM To Point	Backup Guidance LEM Abort Prob.	Backup Guidance LEM Abort Rel.	Backup Guidance LEM To Point
5. C-5 2nd Stage, Manned Veh.		.8301			.1406	.9919[B]	53									
Fuel System	.9978															
Oxidizer System	.9945															
Hydrau. Con. per eng.	.9977															
Auxiliary Power	1.0000															
Electronics & Guid.	.9745															
Airframes & Sep.	.9982															
Prop. Utilization	.9976															
Engines, each	.9732															
6. Circularization man. manned		.9863			.0051	.9919[B]	53	.0074	.7944[C]	55						
Ignite	.9960															
Burn	.9985															
Shutoff	.9991															
Platform & Computer	.9926															
7. Coast in orbit-manned veh.		.9870			.0056	.9919[B]	53	.0074	.7944[C]	55						
Attitude Control	.9994															
Platform & Computer	.9926															
Sextant & Teles.	.9950															
8. Tanker Orient for Rendezvous		.9925			.0075	.9919[B]	53									
Attitude Control	.9999															
Platform & Computer	.9926															
9. Rendezvous Maneuver		.9749			.0251	.99.9[B]	53									
Ignite	.9960															
Burn	.9985															
Shutoff	.9991															
Platform & Computer	.9926															
Attitude Control	.9998															
Ignite	.9960															
Burn	.9985															
Shutoff	.9991															
Radar	.9950															
10. Docking Maneuver		.9795			.0131	.9919[B]	53	.0074	.7944[C]	55						
Attitude Control-T	.9980															
Platform & Comp.-T	.9926															
Attitude Control-M	.9990															
Plat. & Computer-M	.9926															
Mechanical	.9982															
Human Factors	.9990															

[redacted]

[redacted]

	Normal Mode Subsys. Rel.	Normal Mode Step Rel.	Abort Mode Subsys. Rel.	Abort Mode Step Rel.	Normal Guidance CM Abort Prob.	Normal Guidance CM Abort Rel.	Normal Guidance CM To Point	Backup Guidance CM Abort Prob.	Backup Guidance CM Abort Rel.	Backup Guidance CM To Point	Normal Guidance LEM Abort Prob.	Normal Guidance LEM Abort Rel.	Normal Guidance LEM To Point	Backup Guidance LEM Abort Prob.	Backup Guidance LEM Abort Rel.	Backup Guidance LEM To Point
11. Fuel Transfer & Separate		.9835			.0165	.9919[B]	53									
Fuel Transfer	.9853															
Mechanical	.9982															
12. Orient for Injection		.9925			.0001	.9919[B]	53	.0074	.7944[C]	55						
Attitude Control	.9999															
Platform & Computer	.9926															
13. C-5 3rd Stage-Injection		.9333			.0589	.9731[D]	53									
Fuel System	.9978															
Oxidizer System	.9945															
Hydrau. Control	.9977															
Auxiliary Power	1.0000															
Elect. & Guidance	.9745															
Airframe & Sep.	.9982															
Prop. Utilization	.9976															
Roll Control	.9983															
Engine	.9732															
14. Navigation-translunar		.9894			.0032	.9731[D]	53	.0074	.7794[E]	55						
Attitude Control	.9994															
Platform & Computer	.9926															
Sextant	.9975															
Human Factors	1.0000															
Life Support Equip.	.9999															
15. Orient for Midcourse		.9925			.0001	.9731[D]	53	.0074	.7794[E]	55						
Attitude Control	.9999															
Platform & Computer	.9926															
Human Factors	1.0000															
16. Midcourse Man-Main Prop.		.9873			.0042	.9731[D]	53	.0074	.7794[E]	55						
Ignition	.9960															
Burn (2%)	.9996															
Shutoff	.9991															
Platform & Computer	.9926															

[redacted]

[redacted]

	Normal Mode Subsys. Rel.	Normal Mode Step Rel.	Abort Mode Subsys. Rel.	Abort Mode Step Rel.	Normal Guidance CM Abort Prob.	Normal Guidance CM Abort Rel.	Normal Guidance CM To Point	Backup Guidance CM Abort Prob.	Backup Guidance CM Abort Rel.	Backup Guidance CM To Point	Normal Guidance LEM Abort Prob.	Normal Guidance LEM Abort Rel.	Normal Guidance LEM To Point	Backup Guidance LEM Abort Prob.	Backup Guidance LEM Abort Rel.	Backup Guidance LEM To Point
17. Navigation-translunar		.9894			.0032	.9731[D]	53	.0074	.7794[E]	55						
Attitude Control	.9994															
Platform & Computer	.9926															
Sextant	.9975															
Human Factors	1.0000															
Life Support Equip.	.9999															
18. Orient for Midcourse		.9925			.0001	.9731[D]	53	.0074	.7794[E]	55						
Attitude Control	.9999															
Platform & Computer	.9926															
Human Factors	1.0000															
19. Midcourse man.-main prop.		.9873			.0042	.9731[D]	53	.0074	.7794[E]	55						
Ignition	.9960															
Burn (2%)	.9996															
Shutoff	.9991															
Platform & Computer	.9926															
20. Navigate - Translunar		.9894			.0032	.9731[D]	53	.0074	.7794[E]	55						
Attitude Control	.9994															
Platform & Computer	.9926															
Sextant	.9975															
Human Factors	1.0000															
Life Support Equip.	.9999															
21. Orient for Midcourse		.9925			.0001	.9731[D]	53	.0074	.8894[E]	55						
Attitude Control	.9999															
Platform & Computer	.9926															
Human Factors	1.0000															
22. Midcourse Maneuver-Att. Con.		.9916			.0010	.9731[D]	53	.0074	.7794[E]	55						
Attitude Control	.9990															
Platform & Computer	.9926															
23. Navigate-Translunar		.9894			.0032	.9731[D]	53	.0074	.7794[E]	55						
Attitude Control	.9994															
Platform & Computer	.9926															
Sextant	.9975															
Human Factors	1.0000															
Life Support Equip.	.9999															

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	Normal Mode		Abort Mode		Normal Guidance CM			Backup Guidance CM			Normal Guidance LEM			Backup Guidance LEM		
	Subsys. Rel.	Step Rel.	Subsys. Rel.	Step Rel.	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point
24. Orient for Midcourse		.9925			.0001	.9731[D]	53	.0074	.7794[E]	55						
Attitude Control	.9999															
Platform & Computer	.9926															
Human Factors	1.0000															
25. Midcourse Man-Att. Con.		.9916			.0010	.9731[D]	53	.0074	.8894[E]	55						
Attitude Control	.9990															
Platform & Computer	.9926															
26. Navigate for Lunar Retro Man.		.9868			.0058	.9731[D]	53	.0074	.7794[E]	55						
Attitude Control	.9994															
Platform & Computer	.9926															
Sextant & Teles.	.9950															
Human Factors	.9999															
27. Orient for Lunar Retro Man.		.9924			.0001	.9731[D]	53	.0074	.7794[E]	55						
Attitude Control	.9999															
Platform & Computer	.9926															
Human Factors	.9999															
28. Retro Man. to lunar orbit		.9691			.0188	.9982[F]	39	.0074	.3931[H]	55						
Ignition	.9960															
Burn	.9811															
Shutoff	.9991															
Platform & Computer	.9926															
29. Navigation in lunar orbit		.9868			.0058	.9982[F]	38	.0074	.3931[H]	55						
Attitude Control	.9994															
Platform & Computer	.9926															
Sextant & Scanning Tel.	.9950															
Human Factors	.9999															
Life Support Equip.	.9999															
30. Orient for Orbit Transfer Man.		.9924			.0001	.9982[F]	39	.0074	.4140[G]	55						
Attitude Control	.9999															
Platform & Computer	.9926															
Human Factors	.9999															
31. Orbit Transfer Maneuver		.9869			.0046	.9982[F]	38	.0074	.3931[H]	55						
Ignition	.9960															
Burn	.9992															
Shutoff	.9991															
Platform & Computer	.9926															

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	Normal Mode Subsys. Rel.	Normal Mode Step Rel.	Abort Mode Subsys. Rel.	Abort Mode Step Rel.	Normal Guidance CM Abort Prob.	Normal Guidance CM Abort Rel.	Normal Guidance CM To Point	Backup Guidance CM Abort Prob.	Backup Guidance CM Abort Rel.	Backup Guidance CM To Point	Normal Guidance LEM Abort Prob.	Normal Guidance LEM Abort Rel.	Normal Guidance LEM To Point	Backup Guidance LEM Abort Prob.	Backup Guidance LEM Abort Rel.	Backup Guidance LEM To Point
32. Navigate-transfer orbit		.9872			.0054	.9982[F]	38	.0074	.3931[H]	55						
Attitude Control	.9998															
Platform & Computer	.9926															
Sextant & Scann. Tel.	.9950															
Human Factors	.9999															
Life Support Equip.	.9999															
33. Orient for Descent Man.		.9924			.0001	.9982[F]	39	.0074	.4140[G]	55						
Attitude Control	.9999															
Platform & Computer	.9926															
Human Factors	.9999															
34. Descent Maneuver		.9652			.0219	.9721[I]	38	.0074	.3638	55						
Ignition	.9960															
Burn (90%)	.9821															
Shutoff	.9991															
Platform & Computer	.9926															
Radar	.9950															
35. Hover and Letdown Man.		.9622			.0158	.9739[K]	38	.0074	.3645[L]	55						
Mechanical	.9982															
Ignition	.9960															
Burn (10%)	.9980															
Shutoff	.9991															
Platform & Computer	.9926															
Human Factors	.9960															
Altimeter	.9950															
Television	.9950															
Landing Gear	.9920															
36. Lunar Surface Operation		.9928			.0072	.9739[K]	38									
Communications	.9999															
Crew & Science Equip.	.9950															
Life Support Equip.	.9999															
Human Factors	.9980															
37. Lunar Launch		.9739		.9256												
Mechanical	.9982		.9982													
Ignition	.9960		.9960													
Burn	.9806		.9806													
Shutoff	.9991		.9991													
Computer & Platform	.9996		.9500													

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[redacted]	Normal Mode		Abort Mode		Normal Guidance CM			Backup Guidance CM			Normal Guidance LEM			Backup Guidance LEM		
	Subsys. Rel.	Step Rel.	Subsys. Rel.	Step Rel.	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point	Abort Prob.	Abort Rel.	To Point
38. Orbit Determination		.9983		.9492												
Attitude Control	.9998		.9998													
Platform & Computer	.9991		.9500													
Sextant & Telescope																
Life Support Equip.	.9999		.9999													
Human Factors	.9999		.9999													
39. Orient for Escape		.9994		.9498												
Attitude Control	.9999		.9999													
Platform & Computer	.9996		.9500													
Human Factors	.9999		.9999													
40. Escape Maneuver		.9754		.9270												
Ignition	.9960		.9960													
Burn	.9806		.9806													
Shutoff	.9991		.9996													
Platform & Computer	.9996		.9500													
41. Navigation-Transearth Coast		.9983		.9492												
Attitude Control	.9994		.9994													
Platform & Computer	.9991		.9500													
Sextant																
Human Factors	.9999		.9999													
Life Support Equip.	.9999		.9999													
42. Orient for Midcourse		.9994		.9498												
Attitude Control	.9999		.9999													
Platform & Computer	.9996		.9500													
Human Factors	.9999		.9999													
43. Midcourse Maneuver -main prop.		.9943		.9450												
Ignition	.9960		.9960													
Burn (2%)	.9996		.9996													
Shutoff	.9991		.9991													
Platform & Computer	.9996		.9500													
44. Navigate-Transearth Coast		.9983		.9492												
Attitude Control	.9994		.9994													
Platform & Computer	.9991		.9500													
Sextant																
Human Factors	.9999		.9999													
Life Support Equip.	.9999		.9999													

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	Normal Mode Subsys. Rel.	Normal Mode Step Rel.	Abort Mode Subsys. Rel.	Abort Mode Step Rel.	Normal Guidance CM Abort Prob.	Normal Guidance CM Abort To Rel. Point	Backup Guidance CM Abort Prob.	Backup Guidance CM Abort To Rel. Point	Normal Guidance LEM Abort Prob.	Normal Guidance LEM Abort To Rel. Point	Backup Guidance LEM Abort Prob.	Backup Guidance LEM Abort To Rel. Point
45. Orient for Midcourse		.9994		.9498								
Attitude Control	.9999		.9999									
Platform & Computer	.9996		.9500									
Human Factors	.9999		.9999									
46. Midcourse Man.-main Prop.		.9943		.9450								
Ignition	.9960		.9960									
Burn	.9996		.9996									
Shutoff	.9991		.9991									
Platform & Computer	.9996		.9500									
47. Navigate-Transearth Coast		.9983		.9492								
Attitude Control	.9994		.9994									
Platform & Computer, Sextant	.9991		.9500									
Human Factors	.9999		.9999									
Life Support Equip.	.9999		.9999									
48. Orient for Midcourse		.9994		.9498								
Attitude Control	.9999		.9999									
Platform & Computer	.9996		.9500									
Human Factors	.9999		.9999									
49. Midcourse Man.-Att. Cont.		.9986		.9490								
Attitude Control	.9990		.9990									
Platform & Computer	.9996		.9500									
50. Navigate-transearth coast		.9983		.9492								
Attitude Control	.9994		.9994									
Platform & Computer, Sextant	.9991		.9500									
Human Factors	.9999		.9999									
Life Support Equip.	.9999		.9999									
51. Orient for Midcourse		.9994		.9498								
Attitude Control	.9999		.9999									
Platform & Computer	.9996		.9500									
Human Factors	.9999		.9999									
52. Midcourse Man.-Alt. Control		.9986		.9490								
Attitude Control	.9990		.9990									
Platform & Computer	.9996		.9500									

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	Natural Mode		Abort Mode		Natural Guidance CM		Backup Guidance CM		Natural Guidance LEM		Backup Guidance LEM	
	Subsys. Rel.	Step Rel.	Subsys. Rel.	Step Rel.	Abort Prob.	Abort To Rel. Point	Abort Prob.	Abort To Rel. Point	Abort Prob.	Abort To Rel. Point	Abort Prob.	Abort To Rel. Point
53. Separate & Orient for Re-entry		.9974		.9479								
Mechanical	.9982		.9982									
Attitude Control	.9999		.9999									
Platform & Computer	.9996		.9500									
Human Factors	.9999		.9999									
54. Re-Entry		.9843		.9355								
Attitude Control	.9980		.9980									
Mechanical	.9982		.9982									
Platform & Computer	.9996		.9500									
Human Factors	.9920		.9920									
55. Recovery		.9990										
Overall Mission Success Probability			0.2968									
Overall Mission Safety			0.8852									
Disasters/Mission Success			0.3868									
Mission Safety after Step 28			0.8560									

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NOTES 2-Man EOR Reliability and Safety Analysis

A. Escape tower reliability = .9990

B. (Separation) (Orient for Midcourse) (Midcourse maneuver, SM Engine)

C. (Separation) (Orient for Midcourse, backup guidance) (Midcourse, SM Engines, backup guidance) (Orient for re-entry, backup guidance) (Re-entry, backup guidance)

D. (Separation) (Orient for Escape) (Escape)

E. (Separation) (Orient for Escape, backup guidance) (Escape, backup guidance) (Orient for re-entry, backup guidance) (Re-entry, backup guidance)

F. Separate LEM

G. (Separation) (Steps 39 through 54 with backup guidance)

H. (Separation) (Steps 38 through 54 with backup guidance)

I. (Separation) (Step 37)

J. (Separation) (Step 37 through 54 with backup guidance)

K. (Step 37)

L. (Step 37 through 54 with backup guidance)

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APPENDIX C

INDEPENDENT MODE COMPARISONS BY SEVERAL AEROSPACE COMPANIES

During the past year a number of major aerospace companies have carried out extensive company funded systems analyses comparing the several modes for initial Manned Lunar Landings. In all cases, significant advantages for the Lunar Orbit Rendezvous technique were concluded as illustrated by the following direct quotations from the various companies:

BOEING

"The lunar orbit rendezvous (LOR) mode offers definite advantages with respect to mission success and flight safety over the alternate modes of direct flight (DF) and Earth orbit rendezvous (EOR). Although these advantages are coupled to the factors of timeliness and cost in some cases, there are many in which the advantage is absolute. These advantages are partly offset by the unique requirement for accomplishing lunar orbit rendezvous, but this factor does not constitute a serious penalty. In addition to its overall advantage, the LOR mode offers good growth potential for advanced mission applications."

"Attainment of an Apollo mission success probability of 0.90 is predicated on a launch vehicle reliability of 0.95. The LOR mode with its requirements for a single C-5 launch thereby attains an appreciable advantage over EOR (two C-5 launches plus rendezvous and tanking or connecting) or DF (NOVA launch). Attainment of single launch reliability of 0.95 in the 1967 period is a major challenge in the C-5 development program. Although this value might be attained for the time-phased dual launch mission of the EOR mode, or for the NOVA vehicle, it would be at the expense of greatly intensified development effort or the provision of additional backup vehicles."

"The single factor which most strongly favors LOR over EOR or DF is that the Lunar Excursion Module is specifically designed for the landing operation, with no compromise for atmospheric entry. In general, separate development of the LEM and CSM enhances mission success by permitting concentration on design features suited to the unique functions of the individual vehicles. Especially advantageous is the provision for excellent pilot visibility which greatly enhances the likelihood of a successful touchdown. Similarly, the gross size difference of the landing vehicles in the three cases--a 19.3 foot, 10,310-pound LEM versus a 50 to 60 foot, 60,000 pound CSM--will be manifested by large differences in rocket exhaust plume size and resulting surface blast effects at

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touchdown. Since maneuverability is a critical factor in achieving a successful landing, there is qualitatively a considerable advantage for the relatively nimble small landing vehicle."

"Both the EOR mode based on two C-5 launch vehicles and DF mode based on a C-8 NOVA concept require high-energy propellants for the lunar landing propulsion stage. In typical configurations, this stage is also required to perform the prior functions of translunar midcourse correction and lunar orbit injection. The lunar descent and landing maneuver requires at least two additional thrust periods: for deorbit, and landing. Therefore, a considerable portion of the available margin of reliability (0.95 total for the spacecraft) must be assigned this cryogenic, nonhypergolic, throttlable and multiple-restart propulsion system. An extensive development effort would be required to ensure a reliability in excess of 0.984, which is the value assigned to the entire LEM in the LOR mode. In contrast, LEM development may be initiated with Earth storable, hypergolic propellant, landing and lunar launch propulsion systems, and advantage taken of the extensive system development background of these propellants. In addition, the LEM landing stage is not used for translunar corrections or lunar orbit injection, hence the total number of starts for this engine is at least halved."

"Lunar landing (and ascent) guidance system reliability is enhanced in the LOR mode through relative range measurements between the LEM and the orbiting Command and Service Modules (CSM). These measurements, together with those of the inertial navigation and radar altimeter units, permit a three-way internal consistency check which virtually eliminates the possibility of guidance system ambiguity in establishing the prelanding elliptical orbit and timing the deorbit impulse."

"On the debit side in the LOR mode is the requirement for lunar orbit rendezvous and crew transfer prior to transearth orbit injection. However, many factors in the lunar orbit rendezvous support confidence in a high level of success. Thus, the target velocity is much less than in the case of Earth orbit rendezvous--on the order of 5,000 feet per second--which greatly eases launch timing accuracy requirements and results in low closing velocities to facilitate target search and acquisition. Reliability is further enhanced by provisions for complete redundancy of rendezvous guidance and propulsion capability in the LEM and CSM. Thus, either vehicle may control the closing maneuver, and either vehicle may provide the velocity changes necessary to effect rendezvous."

"Although flight safety in the Apollo mission is attained primarily through inherent systems reliability and crew participation, the expected mission success probability of 0.90 calls attention to cases where an abort is required. In all three of the mission modes considered, redundant guidance, control, and life support subsystems permit emergency Earth return, provided adequate propulsion is available. In each case, the propulsive stages employed for the sequence of maneuvers from Earth escape to return provide for emergency return propulsion

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redundancy through the phase of lunar landing. Extension of this redundancy to lunar ascent and trans-Earth orbit injection would require an additional, specifically redundant, propulsion stage in each of the mission modes."

"LOR attains a potential advantage in this regard since, with the growth resulting from the use of high-energy propellants such as OF_2/MMH, the additional LEM propulsion redundancy may be incorporated within C-5 booster limitations. In contrast, Service Module propulsion redundancy in the case of EOR or DF would require Earth escape weights on the order of 350,000 pounds. This value is in excess of the capability of two C-5's or a C-8 NOVA."

CHANCE VOUGHT

"The unique aspect of the LOR mission, which affects mission success and flight safety, is the ascent and rendezvous of the LEM with Apollo. This is not considered today to be the controlling aspect of the lunar mission. Recent studies and simulations carried out in considerably more detail than previously achieved indicate that:

> "Cooperative rendezvous based on orbital mechanics is a more exact and straightforward maneuver than rendezvous based on aero-mechanics as practiced by refueling aircraft and Discoverer retrieval aircraft."
>
> "Cooperative rendezvous about the moon is a more straightforward maneuver than rendezvous about the earth because of the much slower rotation of the lunar launch site under the rendezvous orbit."
>
> "The lack of lunar tracking stations does not substantially lessen the chance of successful rendezvous since the key factor in the Lunar Orbit Rendezvous is the relative tracking of each vehicle on the other."
>
> "Cooperative rendezvous using either automatic, manual, or combined systems appears to be a more straightforward and less difficult maneuver than the lunar descent maneuver, based on real-time manned simulator test programs."

"Perhaps the most significant merit of the LOR mission is that the final lunar landing vehicle is approximately 25 percent of the size and weight of the lunar lander for both the EOR and direct modes. As indicated in the configuration discussion, this smaller lunar lander makes possible a simpler, more straightforward, more reliable landing module with inherently better control and crew vision. This small size and weight makes it feasible to provide ground test facilities that are capable of simulating various portions of the lunar mission."

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CONVAIR

"LOR and DF launch operations are of equivalent or lesser complexity than for EOR. An estimated three to four EOR launch vehicles must be readied simultaneously to acheive a probability of launch phase success comparable to either the DF or LOR mode. Also, EOR launch windows are more critical."

"Critical flight operations include the velocity maneuvers and staging and docking procedures necessary to continue the mission. In the case of EOR, more critical flight operations are required than for the DF or LOR modes; these include second launch vehicle flight, orbital transfer to earth orbit rendezvous, and either docking and checkout of the translunar vehicle or propellant transfer to the translunar vehicle."

"The translunar mission via the DF mode requires either development of a larger Nova-type launch vehicle (using earth-storable propellants for the translunar mission segment), or development of cryogenic stages for the translunar vehicle to permit use of a Saturn C-5 launch vehicle (presently under development). The DF mode, accordingly, has a low probability of mission success since either the launch vehicle or the translunar vehicle to be used would be in an early stage of development, if current mission schedules are observed."

"Abort capability for propulsion system failures occuring after the earth orbit phase depends upon the detail design of each mode. For LOR, abort capability may be enhanced by designing the LEM/CM docking attachment to permit use of the LEM propulsion system as a standby to the SM propulsion system. Such a design would make available both primary and backup propulsion systems for the translunar portion of the LOR mode, equalizing abort capabilities from the translunar orbit."

"Flight safety is higher for the LOR mode in comparison with the other approaches since, in event of LEM primary engine failure, the backup to the failed system is relied upon only until return of the CM, rather than for complete earth return."

"The LOR mode permits the use of a lunar touchdown vehicle designed specifically for the landing phase. This vehicle possesses a low center of gravity, light weight, better vision and, in general, less susceptibility to landing hazards."

"Landings in the DF and EOR configurations can be accomplished by staging a lunar descent module prior to touchdown to reduce the final landing weight. Staging during the critical landing maneuver is a dangerous operation. Despite this staging capability, the landing vehicle still cannot be designed as advantageously for landing as LEM because of mission requirements for an atmospheric re-entry capability."

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"The rescue capability afforded the LEM by the orbiting Command Module/Service Module (CM/SM) affords additional flight safety in case of complete failure of the LEM abort system during the descent and ascent transfer orbits."

"Thus, on the basis of mission success and flight safety considerations, it appears that the LOR mode is more desirable than the DF or EOR lunar landing modes, particularly within the time period specified."

DOUGLAS

"Of the three prominent approaches to the lunar landing mission, the lunar orbit rendezvous (LOR) offers the highest probability of mission success and the greatest degree of crew safety in the shortest time scale. The prime factors to be considered in comparing LOR with other modes of operation are reliability, crew safety, and rendezvous in an unexplored environment."

"Many of the advantages of LOR result from the separation of the Apollo spacecraft into two independent vehicles: one designed for re-entry and the other designed specifically for lunar landing. The Command Module is shaped to meet the aerodynamic requirements of earth launch and re-entry, and the Lunar Excursion Module is shaped to meet the requirements of lunar landing, including the primary requirement of adequate vision for the crew."

"A degree of operational flexibility, including some rescue capability, is provided by the presence of two vehicles, rather than a single vehicle. A desirable communications link with the earth is afforded for far-side landings by the presence of the orbiting Command/Service Module, which also provides a back-up communication link for near-side landings. Various similar equipments, designed for simplified modular installation, provide a measure of redundancy to the two modules; for example, the Command Module Navigation and Guidance computer can backup the LEM computer through use of an RF link. Redundancy is thus provided without the loss of performance which would result if the vehicle had a back-up computer which was carried to and from the lunar surface.

"The LEM is smaller and lighter and provides better handling qualities than a vehicle which could land the Command Module on the moon. Because the smaller vehicle produces less loading of the landing gear, the landing gear and attaching structure are simpler. Its smaller size places the vehicle center of gravity nearer the surface at touchdown, so the vehicle is more stable and less likely to tip over during landing. (Ingress and egress from the vehicle are also simplified.) The C-5 vehicle is capable of boosting this assembly to escape velocity."

"The LOR mode permits landing of approximately the same useful housing and equipment as either of the other two modes. In addition, its more efficient staging characteristics allow the use of storable propellants for all-propulsion

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stages of the Apollo spacecraft. (A cryogenic landing stage, though not recommended, would increase the capability for future growth.)"

"A comparison of the requirements for rendezvous in the LOR and EOR modes shows certain advantages for each. The obvious advantage of EOR is that the rendezvous maneuver is performed near earth, with the assistance of ground-based tracking. However, this advantage is paralleled in part by the good visibility and communications between vehicles in LOR."

"The disadvantage of EOR configurations is that the poor visibility afforded the astronauts during the terminal rendezvous and docking (or propellant transfer) imposes a strong dependency upon instrumentation and automaticity. On the other hand, the LOR technique can utilize a high degree of visibility and the advantages of crew judgment and flexibility in achieving docking."

"With the LOR mode, the C-1B boost vehicle can be used for rendezvous and docking exercises with the actual vehicles in earth orbit at an early date and at minimum cost. These early systems checks and crew training missions increase the total vehicle reliability and probability of mission success."

<u>GRUMMAN</u>

"The LOR mission concept was formulated as a means of obtaining manned lunar landing in the shortest possible calendar time with maximum safety. It requires the least launch-vehicle payload of any mission concept considered, and allows spacecraft design to concentrate on the problems associated with lunar landing and take-off."

"Comparied with LOR, the direct (Apollo) mission requires a longer program due to Nova booster development. It appears comparable in mission safety to LOR, because the lunar rendezvous requirement is eliminated, but the lunar landing becomes more difficult due to increased vehicle size, design limitations imposed by command module (CM) re-entry, and the necessity for staging the lunar landing module (LLM) at hover. The direct (C-5) mission may require increased development time, since the existing Apollo effort would be drastically re-oriented to a two-man CM and cryogenic service module (SM). Mission safety will be lower than for LOR, as a result of decreased system redundancies necessary to meet the severe CM gross-weight limit of 6500 lb. In addition, the landing difficulty of the direct (Apollo) mode also exists."

"Comparing LOR with EOR, the following advantages can be cited for the former:

"Almost 50% reduction in escape payload requirements, which allows one Saturn C-5 per mission instead of two.

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"Mission safety appears to favor LOR, although a more complete comparison of specific designs is required. EOR's major advantage is that mission safety does not depend on successful execution of the rendezvous and docking maneuvers. However, LOR results in a more compact landing configuration which can provide better crew visibility and landing stability, thus improving the safety of executing this critical maneuver. LOR mission safety does depend on successful completion of rendezvous, but sufficient system redundancies can be provided within the weight limitations of the C-5 to provide a high probability of success for this maneuver."

"The LEM design can be based on the critical requirement of lunar landing and of rendezvous, without the restrictions imposed on the Apollo CM by Earth re-entry requirements.

"The development program associated with LOR appears shorter and less costly than that required by EOR, primarily because separate modules are used for the lunar landing and Earth re-entry phases. The compact LEM permits extensive ground testing of landing and rendezvous, using the actual full-scale vehicle in various simulation rigs. In either case, the rendezvous maneuver can be practiced in Earth orbit, but fewer boosters are required for the LOR flight development program."

"LOR offers greater mission growth potential, because the 50% escape payload advantage over EOR is retained as more ambitious missions are attempted. An eventual development in support of high volume lunar operations would employ a nuclear-powered ferry vehicle to shuttle payloads between Earth and Moon, in effect combining both LOR and EOR operations.

"In summary, the LOR mission concept offers significant advantages over all other possible ways of accomplishing manned lunar landing."

LOCKHEED

"Lunar orbit rendezvous permits the launch of a single C-5 for the entire mission. Full advantage is taken of the modular approach to Apollo. Each element can be designed for the use intended in its particular part of the mission. Crew safety is enhanced in that the Command Module (CM) is not exposed to the lunar landing. Finally, and most important for Apollo development, the margin for weight growth can be judiciously controlled to ensure that no compromise in crew safety or system reliability will occur. Adequate design margins can be maintained throughout development. The weight and performance margins are less sensitive in that no module has to be carried through the entire mission velocity change. As a consequence, the need for system modifications incorporating safety changes, which may be uncovered during the flight demonstrations phase, can be accommodated by each module with less potential compromise

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to space vehicle performance. An advantage is the possibility of using additional C-5 launches for logistic support--spare LEM's on the moon, spare Service Modules in lunar orbit, and other supporting activities can be provided. Thus, the Lunar Orbit Rendezvous technique with the C-5 appears to offer the greatest potential for mission success and crew protection in the desired time period."

MARTIN

"Each technique has inherent advantages and disadvantages that are basically independent of the current status of the nati nal space effort. It appears, however, that these must be tempered with consideration of four important points: (1) the Saturn C-5 will be operational long before Nova, (2) reorientation of the basic Apollo CM and SM design approach is undesirable because of potential lost time, (3) it is desirable to use the same propellants in all modules, and (4) the stated national goal dictates a successful manned lunar landing at the earliest possible time."

"The major points of comparison are:

"(1) Spacecraft weights. The LOR technique inherently requires a lower injection weight than either EOR or Direct and requires one Saturn C-5 launch vehicle. EOR requires two. A Nova-class launch vehicle is required for the Direct mission with a crew of three. With a crew of two and using spacecraft propellants which press the state of art somewhat more, the Direct mission could be launched with one C-5. Single launches enhance mission success probability. The minimum lunar landing weight is achieved with LOR.

"(2) Design compromise. Use of LOR allows the CM, SM and LEM to be designed as 'single purpose' modules--the LEM design being based entirely on lunar operations. This permits better visibility, better location of crew members and equipment, simpler display panels, easier thermal control with no reentry problem, and less versatile guidance and control systems. Similar, but converse, advantages result in CM and SM design. The 'single-purpose' modules are less interdependent, so that the whole Apollo is less sensitive to possible changes in design requirements.

"(3) Mission success and flight safety.

"(a) The Direct approach mission tends to have a higher probability of success than either EOR or LOR because the latter two involve all steps of the Direct approach plus one added major step which must work--the rendezvous. This advantage is negated by the increased complexity of a larger launch vehicle if three men are used--or if two are used, by possibly reduced reliability associated with the lower effectiveness of the two-man crew.

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"(b) The rendezvous aspects of EOR tend to be somewhat safer than LOR because EOR is conducted in earth orbit with the 'fail-safe' possibility of reentry if rendezvous is not effected. This difference is alleviated by demonstration of rendezvous in earth orbit test and by providing redundant rendezvous capability in the Command Module and backup guidance in the LEM. Conversely, the EOR approach is less reliable than the LOR because of the requirement for successful operation of two launch vehicles.

"(c) The ability to emphasize the landing in the design of the single-purpose LEM offers a positive safety advantage to LOR for the landing phase of the mission. This is a most significant consideration. Lunar landing is the most critical aspect of the mission.

"Summing up, LOR is preferred over EOR because...

"EOR requires two launch vehicles for mission success.

"EOR's advantage of earth rendezvous over lunar rendezvous is more than offset by the design emphasis that can be placed on the critical landing phase when the LOR concept is used.

"LOR is preferred over the Direct approaches because...

"LOR offers spacecraft propulsion development confidence not available with two-man direct.

"LOR uses presently programmed launch vehicles--not possible with three-man direct.

"LOR permits designing the LEM specifically for lunar operation--not possible with either direct approach.

"The LOR utilizes the full momentum of the present Apollo program and therefore has a distinct timing advantage over any other approach."

NORTHROP

"From the standpoint of mission success and safety, the lunar orbit rendezvous mode of operation shows significant advantages over the other modes considered, such as Earth orbit rendezvous and direct flight."

"The fundamental advantage of the lunar orbit rendezvous mode over the other modes is its considerably lower expenditure of total system energy. That portion of the system required for return to Earth is parked in lunar orbit, thus saving the energy otherwise required for landing on the Moon and return to lunar orbit. This lower energy requirement results in a large reduction in booster size required for Earth launch as compared with the direct

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flight mode, or in a reduction to at least one-half the number of Earth launches required for the Earth rendezvous mode. These reductions can be translated into terms of mission success and safety and lead to other important operational and performance advantages as follows:

"The lunar landing operation requires a controlled vertical approach to an unfamiliar, unprepared surface having many unknown characteristics. An accurate launch must be safely accomplished in this environment by the crew unaided by ground facilities. These lunar operations are considered the most critical portion of the entire Apollo mission. It is imperative that these operations be performed by a vehicle which is not unduly compromised by other requirements, particularly with respect to size, complexity, reliability, and visibility.

"In the lunar orbit rendezvous mode, the Lunar Excursion Module (LEM) is specifically designed for the lunar landing mission and requires only those features necessary for operation in lunar orbit, lunar landing, stay on the surface, launch into lunar orbit, and rendezvous with the Command Module-Service Module (subsequently referred to in this proposal as the CM). Although these requirements are severe in themselves, they result in a light and compact vehicle containing only those propulsion, guidance, control, and life support systems required for this particular mission and the abort modes introduced for safety. In contrast, the lunar landing vehicle for either the Earth orbit rendezvous or direct flight modes must, in addition to requiring those features especially needed for the lunar landing, be capable of performing a direct return to Earth with all those requirements thus imposed for energy expenditure, life support systems, controls, and Earth reentry. These requirements result in a large size and a compromised design for the vehicle. Specifically with the LEM, the crew's capability to conduct the mission successfully is significantly enhanced because of the greatly improved visibility, smaller size, easier control, better access provisions, and reduced complexity. Additionally, the crew can be better trained for the landing and launch operations by the use of the actual LEM."

"The lunar orbit rendezvous between the LEM and the CM is not considered an especially difficult operation. The Gemini program will demonstrate techniques of orbital rendezvous with a manned capsule and a quasi-active target. With the LEM and the CM in lunar orbit, both vehicles will be manned and cooperating. Furthermore, each will possess the operational flexibility to effect the rendezvous. Hence, the probability of success is substantially improved."

"Other advantage of the lunar orbit rendezvous mode are: (1) Only two of the three crew members are subjected to the first lunar landing; the third crewman is able to observe, monitor, and report to Earth the operations from the CM. (2) Certain equipment items in the LEM are identical with those in the CM, permitting their exchange upon completion of the LEM mission. (3) The size and complexity of the Earth launch phase of the mission is greatly reduced."

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"Based on the engineering problems associated with the different modes, and on the present state-of-the-art, availability of equipment and other items under development, development of the LEM should prove less difficult than that required for other lunar-lander vehicles. Since mission success and flight safety depend primarily on these operational and engineering factors, selection of the lunar orbit rendezvous mode of operation for accomplishing the Apollo mission is justified."

REPUBLIC

"During the earth launch phase, excluding any earth-orbital operations, it is considered that the probability of mission success and crew safety is identical for all three approaches on the assumption that timing between successful launch of the EOR injection stage and the spacecraft launching is not critical, and that crew safety is primarily a function of identical emergency abort systems for all approaches."

"The necessity for earth orbit rendezvous may degrade the EOR approach in this phase because of the active docking prior to translunar injection. However, earth tracking and computers may assist this phase for the EOR concept. Assuming, equivalent navigation, life support, etc., equipment, the probability of successful injection is the same for all three modes. Hence there is no difference in crew safety."

"From translunar injection to lunar orbit, crew safety is primarily a function of trajectory accuracy and life support systems which are a part of the command module and common to all three approaches. However, in the LOR approach, the LEM provides additional back-up in these areas for improved crew safety although, under such circumstances, the LEM might be prevented from accomplishing its landing mission. Mid-course corrections during the translunar phase will use the service module propulsion system engine for velocity increments. In the event of failure of the service module propulsion, the ready availability of the LEM propulsion system provides a backup for the velocity increments required for midcourse guidance to assure a free return trajectory and subsequent safe earth reentry. In the other two approaches, the service module provides the backup to the landing stage propulsion, but may require separation of the landing stage before it can serve in this capacity. Hence, for this mission phase, the LOR presents same advantage in crew safety."

"Injection into lunar orbit will differ among the approaches again only by the propulsion thrust and the extra navigation and life support equipment available in the LOR approach, thereby providing an advantage to LOR in this mission phase."

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"In descent to the lunar surface, there is no basic difference between the EOR and DA approach with respect to mission success or crew safety. For LOR, the probability of survival and return to earth of the one crew member remaining in the command module is obviously higher than for the other two members who must land on the surface, or the three man crew descending to the surface in the other two approaches. Hence, partial mission success in the LOR concept could be achieved in the event the descent or ascent phases should be unsuccessful. One of the important advantages of the LOR approach is that the guidance system of the orbiting parent vehicle can serve as an active backup system via a radio link during the lunar landing and take-off operations. This feature will also provide a psychological 'lift' to the crewmen of the LEM."

"On the launch from the lunar surface, the three-man crew of the EOR and DA systems have some advantage by virtue of the added crew member on the surface; however, the two-man crew of the LEM has an advantage of a different type attributable to the third member in orbit where he may monitor and remotely assist in the launch and ascent phases.

"Prior to injection on the return trip to earth, the LOR system is at a disadvantage in that it requires an active docking.

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APPENDIX D

MODE COMPARISON OF POSSIBLE CREW PERFORMANCE DEGRADATION WITH TIME.

Four topics should be considered in an evaluation of performance degradation with time:

1. Degradation of heavy work with time.
2. Degradation of systems monitoring on management tasks.
3. Degradation effects among highly qualified and/or motivated subjects.
4. Performance of highly qualified and motivated subjects in a realistic simulation.

It is beyond the scope of this discussion to attempt to cover all of the literature on performance as affected by time. Rather, an attempt is made to cite selected studies which have special significance to the question at hand. Many of the appropriate studies are not available in original report form, and it is necessary to rely upon secondary sources for purposes of this report.

1. Degradation of heavy work with time. The fact that performance degrades as a function of time spent at a task has been known for a long time. Early studies of production output demonstrated this. Polokov (10) collected data over 52 weeks for industrial plants working a 12-hour day and a 6-day week. The results of this study are shown in figures 1 and 2. Although these are gross measurements of large groups of workers, they give an indication of work output in these conditions.

A study by Goldmark and Hopkins (5) compared performance in a moderately heavy industrial task as influenced by length of work day. The outcome of this study is shown in figure 3. Here we see the difference between the morning and afternoon production and also the degrading performance (after warm-up) as the morning and afternoon progressed. We also see the difference in production between the 8-hour day and the 10-hour day.

These studies involving heavy industrial tasks lead to the following statements:

a. Long hours at tasks produce degraded output.

b. Rest periods can stop degradation and/or improve performance.

c. Long work days (as contrasted to short work days) lead to degraded performance from day to day as the week progresses.

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Presently, with advanced systems such as aircraft, spacecraft, etc., we are still interested in human performance effects upon system output. However, our emphasis has fallen upon other types of tasks, such as monitoring, vigilance, control movements and desicion making as contrasted to heavy manual tasks. However, we cannot extrapolate directly from heavy manual tasks to complex control and intellectual tasks.

2. Degradation of systems management tasks. Adams and Chiles (1) conducted a study at Lockheed-Georgia to investigate the effects of various work-rest cycles upon performance. The schedules used were 2 hours on 2 hours off, 4 hours on 4 hours off, 6 hours on 6 hours off, and 8 hours on 8 hours off for 96 hours (4 days). Their subjects were paid college students. They point out that the subjects working on an 8 on 8 off schedule did better than the other groups on active tasks (arithmetic computation and pattern discrimination), but did poorer on passive tasks in which they respond intermittently (nulling random bias fluctuations in a meter or detecting the absence of an intermitten auditory signal). Plots of these results are shown in figures 4-7.

None of the differences in this study were statistically significant, but the investigators feel that the results are important in that they may indicate that subjects on the 8 on 8 off schedule were challenged by the active tasks as compared to the boredom of the passive tasks, whereas the other groups may have found it easier to maintain higher levels of motivation for the shorter periods of time which they were on duty.

A study was conducted at Air Crew Equipment Laboratory, Naval Air Material Center, by Gaitor et al, (3) in which subjects were confined in a sealed cabin for 7 days on schedules of 8 hours on, 8 hours leisure and 8 hours sleep. Subject performance on one vigilance task (meter nulling) deteriorated progressively throughout the testing sessions, but performance on another vigilance task (responding to a visual warning) did not deteriorate when carried on concurrently with an active task (comprehension of verbally presented material).

Combining the two studies just discussed we may infer that proper task assignment can minimize degradation effects in performance of vigilance tasks and that degradation effects which do occur are probably due to lack of ability to maintain attention and motivation when signals occur infrequently.

Further evidence of differential effects in different types of tasks is noted by Hauty (6), who conducted a study using the School of Aviation Medicine Space Cabin Simulator. This simulator required several kinds of performance. Hauty concluded from his results that tasks having gross discrete cues are more resistant to "fatigue" effects than tasks having minute cues in which vigilance and alertness are important.

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In another study using the Space Cabin Simulator, Hauty (9) reported that with proper work-rest cycling, pilots could maintain adequate performance. When subjects were on a 4 on 4 off schedule they maintained proficiency throughout a 7-day flight. However, in 30-hour runs requiring continuous work without sleep subjects displayed progressive decrement. His conclusion was that "human reliability" cannot be extended beyond 20 hours of continuous work.

3. Degradation effects among highly qualified and/or motivated subjects. Gorham, Orr and Trittipoe (4) conducted a study using two "capable and highly motivated" subjects, each enclosed in a flight simulator. They required the subjects to work 24 hours continuously without sleep. The tasks they performed were designed to produce measures of eye-limb coordination, problem solving, estimation of closure rates, selection and manipulation of controls and constant assessment of environmental conditions within and outside the simulators. A total of seven measures of subject performance were taken and all indicated a trend to improved performance peaking at 6-8 hours and falling off slowly to a low point during the final two or three hours of the test. These authors conclude that the highly motivated subjects delayed the low point as compared to studies in which "garden variety" subjects are used and low and degraded performance is obtained at 6-8 hours on duty.

Another related study conducted by Adams and Chiles (2) using 2 operational B-52 crews produced some interesting results. In this study the same tasks were performed as in the previously reported study by the same investigators (1), but the crews were on a 4 on 2 off schedule for 15 days continuously. Adams and Chiles note that when data for all subjects are combined, the means show a day to day decrement in arithmetic computation, monitoring meters, auditory vigilance, no change in response to warning lights and improvement in pattern discrimination. (See Figure 8.) However, they observed differences between groups and individuals which are interesting in terms of different motivation. After the experiment was in progress it was found that one of the crews (Group A) had been called back from military leave in order to participate as subjects in the experiment. The other flight crew (Group B) had volunteered. Adams and Chiles proposed that Group B was more highly motivated than Group A, and that this is reflected in their relative performance on two of the tasks. (See Figures 9 and 10.)

They also noted that performance of two of the subjects in Group B was only minimally affected by the conditions of the study, and they maintained high performance levels on most of the tasks throughout the test run. (Performance decreased significantly for both on the auditory vigilance task and for one in the arithmetic computation task.) Further, in a post-study interview a majority of the subjects indicated that they could have continued on this schedule for at least another 15 days, if it were necessary and important.

From this study Adams and Chiles conclude that with proper selection crews could maintain acceptable performance levels on the 4 on 4 off schedule for two weeks or longer.

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There is no evidence from closely controlled experiments comparing high and low motivation subjects on performance of space flight and lunar landing mission tasks. However, there is considerable evidence that individual differences in motivation and other traits produce significantly higher performance levels in "capable and highly motivated" subjects, on tasks that have the same basic elements as space flight tasks.

4. Performance of highly qualified and motivated subjects in a realistic simulation. A study has recently been completed by Martin-Baltimore (8) in which 3 test pilots performed 2-3½ day missions which terminated at lunar landing and a 7-day mission including lunar landing and earth return and re-entry. In this discussion we will limit our remarks to the 7-day mission.

The subjects were confined in a command module of the same general configuration and size as the proposed Apollo command module. From this command module the pilots could crawl through a tunnel to a one-man lunar excursion module simulator. All relevant displays and readouts were driven by analog computer with input from pilot controls. The environment was normal sea level and the pilots were on a work-rest cycle approximating 4 on and 4 off.

In order to compare Lunar Orbit Rendezvous and Direct Flight, the following schedule was used:

(1) From pre-launch to lunar orbit the mission was primarily scheduled and carried out as a 3-man direct flight. (Each pilot performed one of the programmed midcourse corrections.)

(2) Each of the three pilots performed a lunar landing and ascent to lunar orbit in the 3-man command module.

(3) Each of the 3 pilots performed a lunar landing, lunar ascent and rendezvous in the lunar excursion module.

(4) Each pilot performed one of the trans-earth midcourse corrections and each performed a re-entry.

Prior to the mission each pilot had had opportunity to train on the simulator and reach an acceptable level of performance for each of the control tasks, and base line data was collected, for purposes of comparison, from these training trials. All attitudes and thrust (where applicable) from earth launch through re-entry were controlled manually. (One exception was that the excursion module was automatically stabilized during rendezvous.)

For purposes of this discussion we will summarize only the results of performance at lunar landing and lunar rendezvous. In an actual mission these maneuvers will come at a time when the pilots will have been through a period of prolonged stress and limited rest. In a simulation, practical limitations determine the

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degree to which stress of the actual flight can be approached. However, this simulation is the closest thing possible to an actual flight at this time. (See Tables I and II.)

Two aspects of the tables stand out:

(1) With one exception, performance does not degrade significantly from preflight to inflight.

(2) For the most part, performance is poorer in the excursion module than in the main module; for example, descent rates maintained for the excursion module were approximately 12 f/s, as opposed to 8 f/s for the main module. Those who conducted the study explain that this was due largely to poor design of instrument displays in the excursion module and that the landing task is substantially the same for both modes otherwise. (These were instrument landings, with no optical or visual displays.)

Those who conducted this study concluded, after evaluation of performance data for all mission phases, that there was no pilot performance decrement which could be attributed to confinement or the task routine and schedule. Medical and psychological evaluation also indicated that the crew had not been adversely affected by performance of the 7-day mission.

RELATED RECENT STUDIES

Three other studies have been recently completed and are in the data analysis phase.

One study, to evaluate various atmospheres, was conducted at Republic Aircraft and used 4 groups of 6 paid college students as subjects. They were confined, one group at a time, in an atmospheric chamber (a large room in this case) and performed many psychomotor tasks, including tracking, meter monitoring, arithmetic computation, pattern discrimination, and others. Each group was subjected to a different atmosphere for the 14 days they were inside the chamber. The atmospheres were:

(1) Normal

(2) 100% oxygen at 3.5 psi

(3) 100% oxygen at 5.0 psi

(4) 100% oxygen at 7.5 psi

The subjects were in normal clothing and worked $3\frac{1}{2}$ hours each day at the performance tasks. The rest of their waking time was spent in medical and physiological evaluation and leisure activity. The investigators report that a preliminary analysis of the data indicates no deficit in performance due to the confinement and atmosphere.

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Another study at USAF School of Aviation Medicine was carried on to investigate problems associated with water balance. Two pilots were confined in an atmospheric chamber, 100% oxygen at 5 psi. They wore the modified Mercury pressure suit (removable limbs) and had schedules of 5 hours on 7 hours off. During duty time they performed various psychomotor tasks including pattern discrimination, vigilance, problem solving, and memory. This study was terminated at 13 days and the investigators report that preliminary analysis shows no performance decrement.

Ames Research Center (11) recently completed a habitability study in which two subjects (a test pilot and a Ph.D physiologist) were confined in a two-man Apollo shaped capsule for 14 days with normal atmosphere and normal clothing. This study was designed to detect performance and/or medical-physiological changes due to confinement in limited space. The capsule allowed $61\frac{1}{2}$ ft^3 per man. The subjects worked on a 4 on 4 off schedule. Although detailed analysis of the data remains to be done, the investigators state that preliminary analysis reveals that the subjects were able to sustain expected levels of performance throughout the test. There was an indication of increasing loss of skeletal calcium (which proper exercise could alleviate) and one of the subjects had great difficulty staying awake during his early morning duty.

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Conclusions and Implications

1. Although manual and heavy task performance degrades as a function of time, it does not necessarily follow that systems management and control tasks degrade in the same manner.

2. Certain kinds of tasks are more susceptible to degradation: a) Performance of tasks based on gross and discrete and frequently occuring cues do not degrade as readily with time as do tasks based on minute and intermittent cues. This of course assumes that cues in the first case do not come so rapidly as to "overload" the subject. In other words, a subject can be either "overloaded" or underloaded. b) Tasks requiring "active" participation (examples: control tasks and problem solving) on the part of the subject are less apt to degrade than tasks in which the subject is passive, (example: monitoring and nulling meter bias, auditory or visual vigilance).

3. Highly motivated subject can delay or eliminate many degrading effects.

4. Experiments evaluating the effects of time, confined space, varying atmospheric conditions and work rest cycles indicate that with proper selection of personnel, systems management and control tasks can be performed at acceptable levels.

5. The "highest fidelity" simulations, presently available at lunar missions, do not discriminate significant differences in pilot performance levels between pre- and inflight conditions.

6. With proper task assignment and equipment design it seems likely that pilot performance can be sustained at required levels for missions up to two weeks at least.

7. The foregoing statements are fair indicants that pilot performance is not a limiting factor for either direct or lunar orbit rendezvous missions.

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TABLE I

Performance Measures for Lunar Landings*

	Lunar Excursion Module		Main Module	
Pre-Flight	$\dot{x}$ (f/s)	$\dot{h}$ (f/s)	$\dot{x}$ (f/s)	$\dot{h}$ (f/s)
Subject A	25.1	32.3	5.4	4.1
" A	5.0	14.7	5.1	3.7
" A	4.2	7.4	8.8	6.7
" B	9.3	7.1	7.9	5.9
" B	10.1	7.6	7.9	5.9
" B	10.3	8.0	6.5	4.8
" C	40.0	2.3	19.2	13.8
" C	2.0	19.2	5.7	4.1
" C	4.1	4.0	4.4	3.1
Mean	12.2	11.4	7.9	5.8
In-Flight				
Subject A	8.0	8.4	5.5	4.2
" B	57.7	7.1	Aborted	Aborted
" C	3.2	16.0	4.5	3.3
Mean	22.9	10.5	5.0	3.7

*The pre-flight measures are based on the last three training trials for each subject.

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TABLE II

Performance Measures for Lunar Rendezvous*

	Displacement (Ft)	Closing Velocity (Ft/Sec)
Pre-Flight		
Subject A	1.7	1.4
" A	6.1	1.7
" A	1.3	.9
" B	1.6	.8
" B	2.4	2.0
" B	1.3	.8
" C	Data not available due to equipment failure	
" C	" " " " " " "	
" C	.8	.6
Mean	2.2	1.2
In-Flight		
Subject A	2.9	.9
" B	3.3	1.5
" C	2.1	.9
Mean	2.8	1.1

*The pre-flight measures are based on the last three training trails for each subject.

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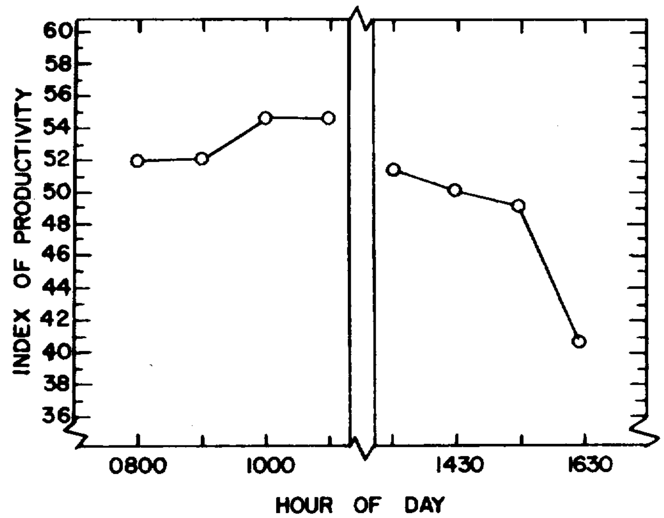

Figure 1. -- Average productivity at different hours of the work day.

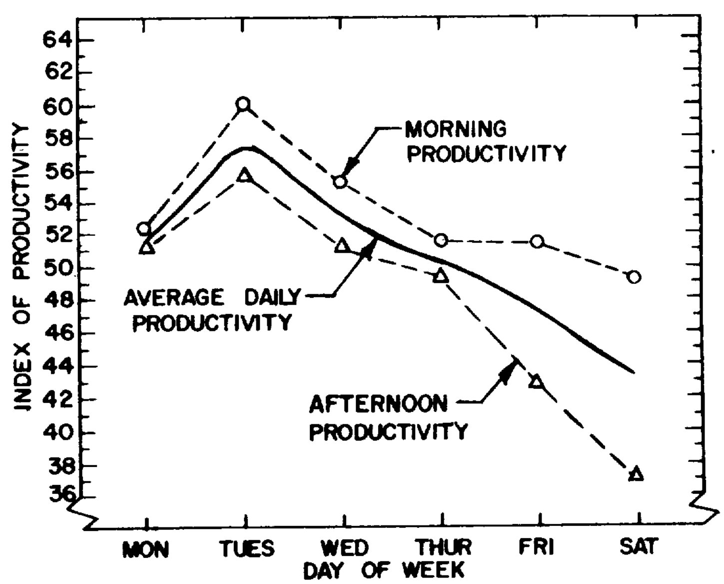

Figure 2. -- Morning, afternoon, and average daily productivity over the days of the work week.

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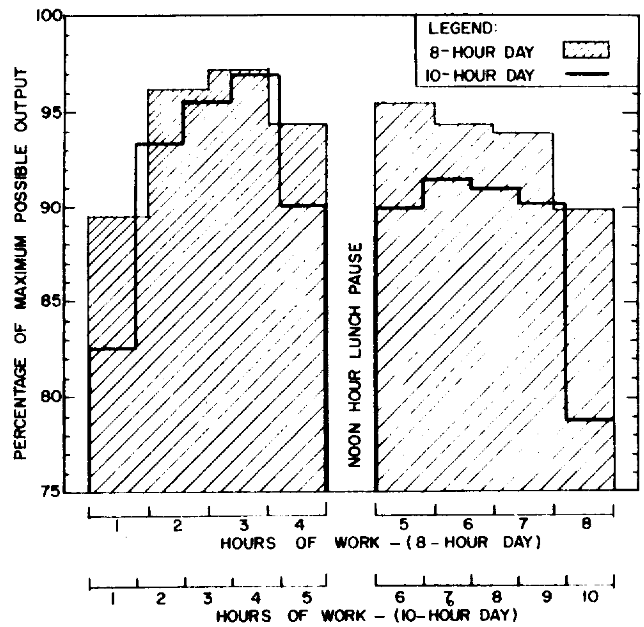

Figure 3. -- Percentage of maximum possible output achieved at different hours in two moderately heavy industrial manufacturing plants. The plants were essentially identical, except that one was worked on an eight hour shift and the other was worked on a 10 hour shift. The average output for the 10-hour day was 90.3 per cent of maximum, the average for the 8-hour day was 94 per cent.

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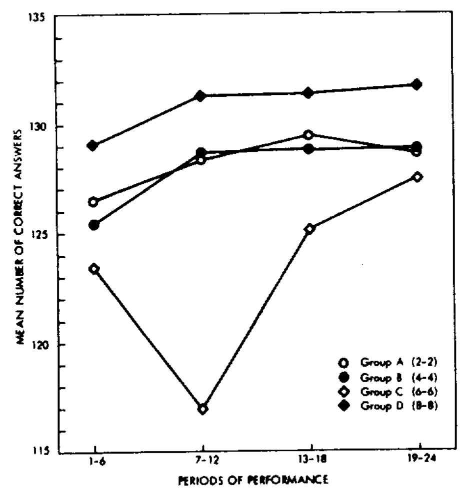

Figure 4. Performance Curves Obtained for the Arithmetic Computation Task.

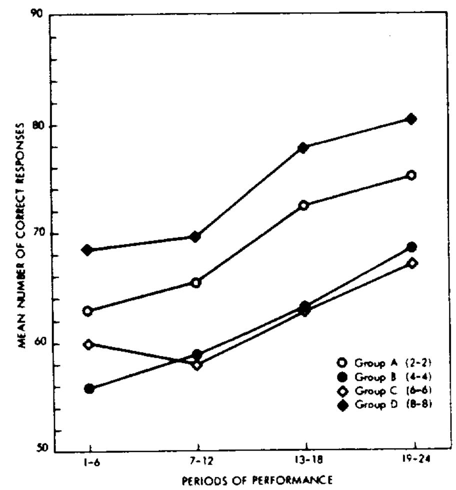

Figure 5. Performance Curves Obtained for the Pattern Discrimination Task.

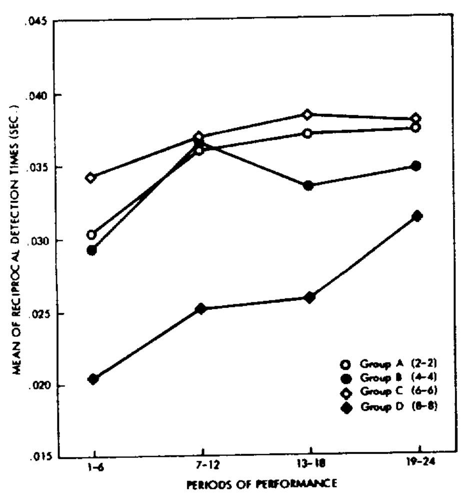

Figure 6. Performance Curves Obtained for the Probability Monitoring Task (Detection Time).

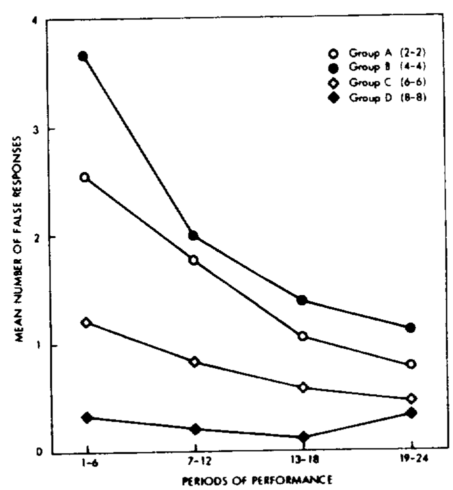

Figure 7. Performance Curves Obtained for the Probability Monitoring (False Responses).

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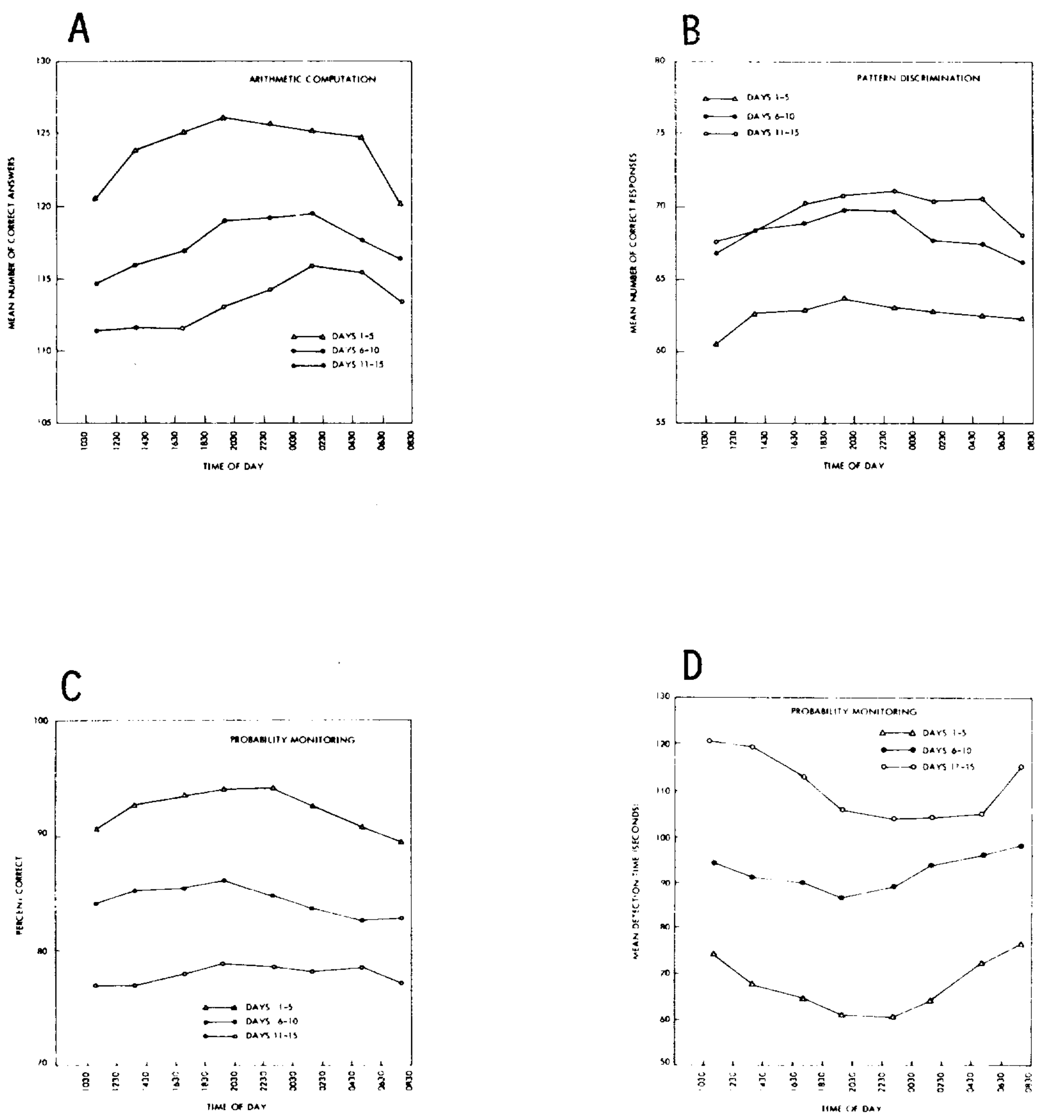

Figure 8 (A through D). Within-day changes in level of task performance

[redacted]

[redacted]

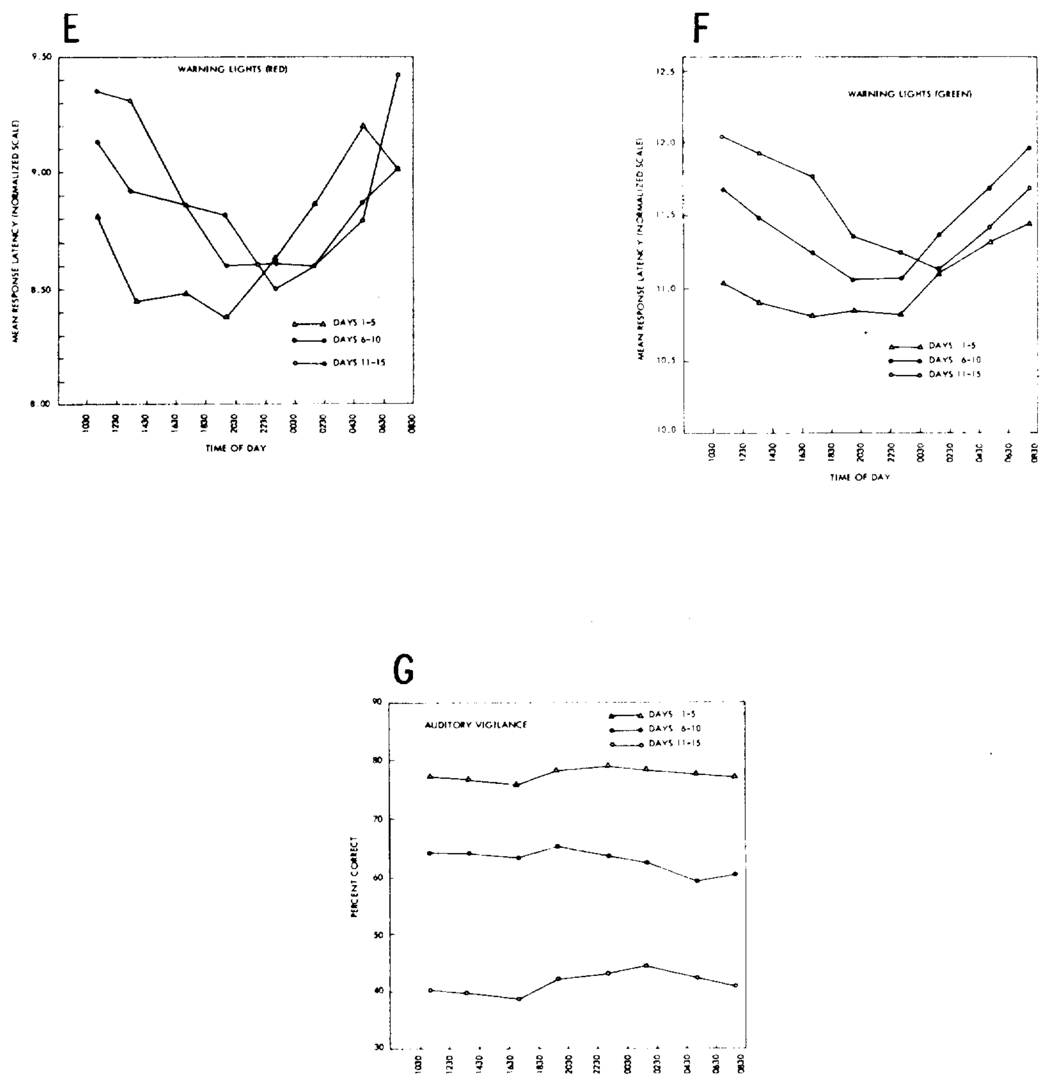

Figure 8 (E through G). Within-day changes in level of task performance

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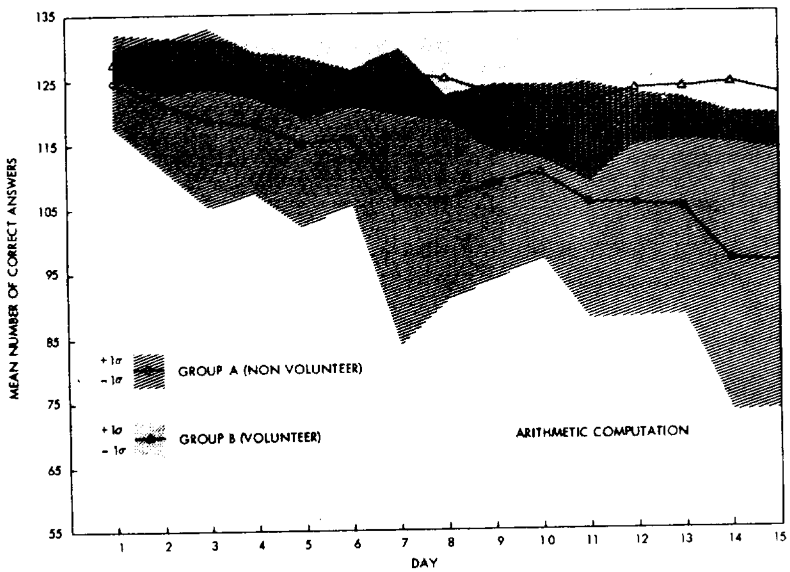

Figure 9. Comparison of Groups A and B in terms of the mean and standard deviation of arithmetic computation task scores for each day of the study

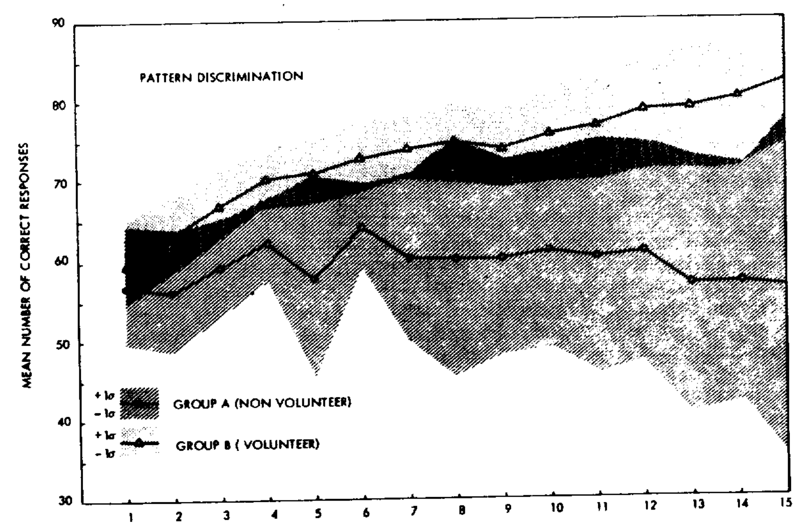

Figure 10. Comparison of Groups A and B in terms of the mean and standard deviation of pattern discrimination task scores for each day of the study

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APPENDIX E

EFFECTS OF THE APOLLO MODE CHOICE ON NATIONAL SPACE CAPABILITY

One purpose in undertaking the manned lunar landing program is to provide a focus for an accelerated development of U. S. space technology. It is therefore appropriate to compare the various Apollo modes in terms of their potential contribution to other civilian and military space programs.

The national space capability may be subdivided into three areas:

1. Payload capability
2. Operational techniques
3. Specific hardware

Possible effects of the Apollo mode decision in each of these areas are discussed below. Three Apollo modes are considered:

1. Lunar Orbit Rendezvous (LOR)
2. Two-man Earth Orbit Rendezvous (EOR2)
3. Two-man, C-5 Direct Flight (DF2)

Payload Capability

Selection of either LOR or DF2 would limit the national payload capability to approximately 230,000 lbs. in earth orbit and 90,000 lbs. to escape during the period 1967-1970. These figures represent the performance of a single C-5 launch vehicle. The EOR2 mode would raise these limits to approximately 450,000 lbs. in orbit and 150,000 lbs. to escape by developing the ability to rendezvous two C-5 payloads. In either case, the limits would apply until nuclear upper stages and/or the NOVA vehicle attain operational status. Present schedules indicate both will be operational in 1971.

Since the choice of EOR2 involves some penalties for the Apollo program, it is desirable to examine the potential requirements for this increased payload capability during the 1967-70 time period. Potential requirements arise from two sources, the DOD and NASA. The attached table summarizes the requirements for launch vehicles as generated by NASA. (The DOD requirements are not expected to call for a payload capacity in excess of 30,000 lbs. over the projected time span; these requirements are cited in the report of the Large Launch Vehicle Planning Group, the last official summary of launches submitted by DOD.) Although the number of launches is probably optimistic, the table does summarize the payload ranges required to meet the various program needs. The Air Force is presently generating a new long range launch schedule, and informal discussions with DOD and Air Force officials indicate all proposed payloads to be well within the capability of a single Saturn C-5 or smaller vehicle.

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The NASA Offices of Applications, Advanced Research and Technology, and Space Sciences, similarly require a large number of launches providing orbital payloads up to 30,000 lbs. for their various missions. A few Saturn C-5 vehicles also are required by the OART program for the development of a nuclear stage. The Office of Manned Space Flight has programmed some Saturn C-1 and C-1B launches for earth orbital flights of Apollo components, for possible Lunar Logistics System flights, and for possible Manned Space Station operations. The Saturn C-5 launches in the OMSF program are primarily for the manned lunar landing missions; however, additional vehicles are shown for possible Lunar Logistics System and Space Station uses.

As the table indicates, no specific requirements exist for payloads in the 230,000 - 450,000 lbs. category during this time period. The choice of DF2 would not change the numbers significantly, but EOR2 would show requirements for a least six C-5 vehicles per year above the figures shown.

It is concluded that there are no planned programs other than the manned lunar project itself which could make use of the larger payload capabilities.

Despite the lack of any known requirements, there remains a possibility that such requirements may develop prior to 1971. It is difficult, if not impossible, to analyze this possibility in detail. It is noted, however, that most of the operational techniques which would be required for such a program would be developed in the LOR mode, and many of them are also necessary for DF2. These techniques are discussed in the following section.

Operational Techniques

The three modes under consideration require the development of a number of operational techniques which are not part of our current capabilities. These techniques are:

1. Ability to launch within a narrow time window. This ability must be developed for all three modes, and is necessary due to lunar launch requirements.

2. Ability to maneuver in earth orbit. Required for LOR and EOR2, but not DF2.

3. Ability to track two vehicles in earth orbit simultaneously. Required for LOR and EOR2, but not DF2.

4. Ability to navigate in space. Required for all modes.

5. Ability to dock vehicles in space. Not required for DF2. LOR requires more precise docking and greater structural integrity than does EOR2, because LOR applies thrust to the mated vehicles.

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6. Ability to transfer fluids in space. Required for EOR2 only.

7. Ability to transfer crew members in space. Required for LOR only.

8. Ability to maintain a functioning crew in space for periods up to two weeks. Required for all modes.

9. Ability to check out and ignite large engines in space with a small crew. Required for all modes.

In summary, rendezvous operational techniques would be required for both EOR2 and LOR, but not for DF2. The EOR2 mode requires the development of fluid transfer techniques, while LOR requires crew transfer techniques and greater structural integrity. All of these capabilities have possible application to other civilian and military programs.

Specific hardware

It is difficult to predict the extent to which specific hardware developed for one program might be applicable to others which are as yet undefined. Experience to date has been mixed. The Atlas booster, for example, has been successfully modified to perform the Mercury mission. The Gemini spacecraft, on the other hand, is virtually a new development, although it was originally viewed as an upgrading of the Mercury capsule. Many other examples of both types could be cited.

The following specific hardware items might be expected to have applicability to other programs without extensive modification:

1. C-5 launch vehicle. Required for all modes.

2. LOX tanker. The LOX tanker developed for EOR2 might be applicable to other programs, although it could not be utilized profitably for other fluids.

3. Spacecraft. The LOR mode requires a three-man spacecraft which is potentially more useful than a two-man vehicle for space stations and lunar bases, where crew rotation presents a sizeable logistics problem. A less likely possibility is the use of the LOR "bug" as a military satellite inspection vehicle operating from a permanent space station.

4. Rendezvous guidance systems and docking structures. The sensors and computers used for rendezvous and the docking structures developed for either EOR2 or LOR probably would not be applicable to other programs without extensive modification.

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5. Expanded ground tracking, computation and control facilities. No significant differences between modes.

6. Expanded launch facilities. The greater launch requirements of the EOR2 mode might force a larger capability at Canaveral.

In summary, the more probable and significant advantages in terms of specific hardware are the three-man spacecraft (LOR) and the LOX tanker (EOR2).

Conclusions

It is concluded that the major differences among the modes in terms of their potential contributions to other programs are:

1. EOR2 provides a greater payload capability, but there are no known requirements for the larger payloads.

2. EOR2 and LOR provide an ability for earth orbit rendezvous which has potential application to space station and military inspection programs.

3. EOR provides a LOX tanker and fluid transfer techniques which might be applicable elsewhere.

4. LOR provides crew transfer techniques which will be a requirement for space stations.

5. LOR provides a three-man spacecraft which is potentially more useful to other programs than the two-man vehicle required for EOR2 and DF2.

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National Launch Vehicle Requirements

User	Equivalent Payload 100 n. mi.	Vehicle	'67	'68	'69	'70
OA, OART, OSS	< 10,000 lbs.	Var.	82	80	69	60
OA, OART, OSS	10,000 - 30,000 lbs.	C-1 B	6	10	10	9
OART	30,000 -230,000 lbs.	C-5	2	3	3	1
OMSF	10,000 - 30,000 lbs.	C-1, C-1B	19	10	11	12
OMSF	30,000 -230,000 lbs.	C-5	7	11	15	13
All	> 230,000 lbs.	--	0*	0	0	0

* Earth orbit rendezvous would show requirements for at least six additional vehicles per year and an equivalent payload of 450,000 lbs.

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